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1931-1932.

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THE INSTITUTION OF PETROLEUM TECHNOLOGISTS

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A medal and a prize of five guineas is awarded annually by the Council to that Student Member of the Institution who shall, in their opinion, have presented the best paper during the session.

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The Fund is raised by voluntary annual subscriptions, donations, and bequests, and all contributions should be sent to the Secretary of the Institution at Aldine House, Bedford Street, London, W.C. 2. The Fund is administered by the Council through the Benevolent Fund Committee, and all applications in connection therewith must be made on a special form which can be obtained from the Secretary of the Institution.

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Advertisements. Advertisements are inserted in the Journal, and information as to terms, etc., can be obtained from Mr. Thomas Tofts, 301-302, Bank Chambers, 329, High Holborn, W.C. 1. (Telephone No. Hol. 4776.)

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PERSONAL NOTES OF MEMBERS AND SPECIAL NOTICES.

It is suggested that members send information regarding their movements to the Secretary, for insertion under this heading.

Mr. E. B. F. AULD has left for Persia.
Mr. S. W. COOKE is leaving for Persia.
Mr. E. H. DOVE is home from Venezuela.
Mr. A. E. DUCK has left India and is now in Burma.
Mr. G. W. LEPPER is home from Burma.
Mr. A. N. LUCIE-SMITH is coming home from Venezuela.
Mr. F. A. MARR is home from Assam.
Mr. H. H. MARTIN has left Ecuador and is returning to England.
Mr. N. MATHESON is now in Venezuela, having left Trinidad.
Mr. P. MEYER is coming home from Persia.
Mr. W. MOORE is home from Iraq.
Mr. M. A. RUST is in Iraq.
Mr. F. S. SMITH has returned to Mexico.
Mr. P. A. STIFF is home from Persia.
Mr. C. THOMAS has returned to Assam.
Mr. D. WOOD has returned to Venezuela.

The Secretary would be glad to hear of the whereabouts of the following members:—C. A. BAUDUIN, A. E. O. COOKE, L. B. HOLLOWAY, C. E. JOBLING, NAND LAL PASI, W. E. SHEPHERD, R. K. VAN SICKLE and F. E. G. WATSON.

DINNER CLUB.

The attention of members is drawn to the Dinner Club of the Institution. This Club holds informal dinners after each General Meeting of the Institution and members may invite guests. Those desiring to receive notice of these dinners are requested to inform the Secretary of the Institution.

THIRTEENTH ANNUAL DINNER.

THE THIRTEENTH ANNUAL DINNER of the Institution of Petroleum Technologists will be held at the Connaught Rooms, London, on October 9th, 1931.

NOMINATIONS FOR MEMBERSHIP OF THE INSTITUTION OF PETROLEUM TECHNOLOGISTS.

The following have been nominated for membership of the Institution of Petroleum Technologists and their Application Forms may be seen at the Offices of the Institution:—

As Members.	PROPOSED BY	SECONDED BY
SPRAKE, Cyril Harding, Engineer, Anglo-American Oil Co., 36, Queen Anne's Gate, London, S.W. 1.	F. H. Garner.	A. Hamilton.
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REYNARD, Herbert Corner, Chemist, Shell Marketing Co., Brill Street, Fulham, London, S.W. 6	J. Kewley.	J. S. Jackson.
As Transference to Associate Members:—		
WALKER, Joseph Edwin, Chemist, Messrs. Moore & George, Ltd., 181, Queen Victoria Street, London, E.C. 4	Harold Moore.	R. B. Hobson.
As Associate:—		
READ, Alfred Leonard, Chemist, Sternol, Ltd., Royal London House, Finsbury Square, London, E.C. 2	Harold Moore.	C. F. Lloyd.

THE INSTITUTION OF PETROLEUM TECHNOLOGISTS.

THE ONE HUNDRED AND THIRTY-SECOND and the ONE HUNDRED AND THIRTY-THIRD GENERAL MEETINGS of the Institution of Petroleum Technologists were held at the House of the Royal Society of Arts, John Street, Adelphi, London, on January 13th and February 10, 1931, respectively. The Chair was taken on both occasion by the PRESIDENT, Dr. A. E. DUNSTAN.

The Secretary read the names of members elected, as follows, and also the names of the candidates nominated for election :—

The following were elected on January 13th, 1931 :—

As Members.—Percy George Hamnall Boswell, Ionel I. Gardescu, William Ladislas Gomory, Eric Stanley Hillman, Edward Alfred Hunting, Arthur John Wright.

As Associate Members.—Roland Edward Hales, Harold Leslie Lyne, James Ness Rodger.

As Transference to Associate Member.—Herbert Richard Lovely.

As Student.—Laurence George Melville Roberts.

As Associates.—Thomas Moore Hickman, John Arthur Reed Petter.

The following were elected on February 10th, 1931 :—

As Members.—Robert Illtyd Lewis, Arthur Richard Pattisson, Jack Francis Mahon Taylor, Sijbren Tijmstra.

As Transference to Member.—Mostafa Allam.

As Associate Members.—William Lawrence Bouch, Richard Godfrey, Arthur Henry Goodliffe, Vacey Vivian Linnington Hope, Herbert Leonard Joseph Hunter, Eric Rofe Styles, Alfred Reginald Thomas.

As Transference to Associate Members.—Norman Macdonald Brodie, Kenneth Brebner Ross, Geoffrey Stewart Taitt.

As Students.—Michael Abramovitch, Geoffrey Melvin Barrett, Arthur Evans, Percival George Higgs, Giles Philip Eliot Howard, Hugh John Marks, Leslie Benjamin Sweetland, William Roy Wright.

As Associates.—Adolph Freiman, Michael Hamel-Smith, Malcolm Alexander Campbell MacNeill.

At the One Hundred and Thirty-Third General Meeting the proposed alterations to the By-Laws, as recommended by the Council, were read, and the President announced the names of the officers elected for the Session 1931–1932.

THE PRESIDENT said that the programme of a Symposium on Salt Domes was a very interesting one, dealing with a fascinating and complicated subject. He suggested that the first meeting should

be devoted to the presentation of short summaries of the various papers and that the second meeting be allocated to a general discussion of the whole subject. For the present it had been decided not to include any discussion of a geophysical nature, but it was hoped on a future occasion to raise that matter as a separate symposium.

The following papers were then presented :—

SYMPOSIUM ON SALT DOMES.

Salt Domes of North Germany.

By James Romanes, F.G.S. (Member).

Although the mere words "salt domes" tend to carry the oil geologist's mind to the Gulf Coast, Persia or Rumania, the fact nevertheless remains that the great plain of North Germany is the real classic salt dome area.

So much has been written on the salt deposits and salt domes of this area that to attempt any general compilation on the subject is beyond the scope of what is merely a contribution to the introduction of a discussion on salt domes. It would appear, therefore, most useful to ignore detail and rather lay stress on the broader facts which the study of this area has brought out. Probably in any discussion of salt dome geology and its bearing on oil the questions of greatest interest are as follows :—

1. The age of the salt.
2. The form of the domes and their tectonic relations to the surrounding sediments.
3. The mechanics of salt dome formation.
4. The influence of salt domes on the formation and concentration of petroleum.

Although the real incentive to the detailed work which has been carried out in this area has been the quest for the valuable potash salts contained in the salt series and only to a lesser degree the quest for oil, yet this classic area throws light on all the above questions.

It is proposed, first of all, to give a brief outline of the geological history of the area, and then discuss shortly the bearing of the German salt domes on these questions.

Geological History.—It is perhaps not generally recognised that the salt deposits of North Germany form part of what is probably the greatest deposit of salt ever laid down on the earth's surface,

and although so much attention has been focussed on the Gulf Coast region of America, it is almost a minor phenomenon compared with that of Northern Europe, so far as salt deposition goes.

The basin in which this salt was ultimately precipitated was formed by the Hercynian folding which followed the close of carboniferous times. It stretched from Eastern England across what is now the North Sea, through Holland, North Germany, Poland and on into Russia. How far this formed one vast inland sea or was broken up into a series of smaller and perhaps disconnected seas, it is hard to say. The earlier deposits in this basin in Germany were conglomeratic continental deposits of considerable thickness —the Rotliegendes. It was in Upper Permian (Zechstein) times that the desiccation of this inland sea gave rise to the great series of salt and allied deposits. It is interesting to note here that Zechstein salt of Germany is represented in this country by the magnesian limestone which outcrops from just east of Nottingham to the coast between the Tees and the Tyne and forms such a well marked topographic feature. This magnesian limestone is, in fact, the marginal facies of the salt deposits, and the western coast of the basin was probably formed by the Pennine Range since, to the west of that Hercynian fold, the Permian rocks are of a totally different facies.

Over the Zechstein salt in Germany was deposited a very complete series of Triassic rocks, probably totalling at least 3000 ft. Bunter, Muschelkalk, Keuper and Rhaetic, which show an alternation of Continental and Marine facies. A long period of submergence must then have taken place with here and there local uplift and denudation, during which time, on the whole, a very complete sequence of the Jurassic, Cretaceous and Tertiary beds were laid down in the northern part of the basin. These deposits probably total 10,000 ft. or so. In the main these are marine sediments with, in the lower part, rather a dominant clay and shale facies, but with a well marked esturine or fresh water development in the highest Jurassaic and lowest Cretaceous closely corresponding to the British development.

In the northern part of the basin a very thick development of Tertiary beds up to 3000 ft. was laid down. This, then, is very briefly the geological conditions of the North German plain.

The Form of the Domes and their Tectonic Relation to the Surrounding Sediments.—Not the least interesting feature of the German basin is the fact that it shows a complete gradation from the normal bedded salt to the typical circular intrusive dome. As might be expected, the normal bedded phase characterises the margin of the basin. For example, in Thuringia, potash is being exploited in almost horizontally bedded salt underlying thick Triassic deposits.

Similarly in the west this same phase has been proved by deep borings as at Winterswijk, in Holland, near the Dutch-German frontier. In this belt the salt series behaves as a normal sedimentary deposit, showing in places normal folding which merely gives rise to salt anticlines. The next step that can be traced is the salt anticline with a thickening of the salt along the crest, but probably with no penetration of the overlying sediments. The classic example of this is Stassfurt. These structures naturally follow along lines of tectonic folding giving rise to elongated thickened masses of salt rather than anything approaching the true dome formation.

A further stage is where the salt begins to penetrate the overlying beds, so that the anticlinal structure is no longer complete till finally we arrive at the true salt dome or plug.

Donald C. Barton[1] gives the following classification for these progressive stages of development from the normal bedded salt:—

(a) Stassfurt type—thickening along anticlinal axes with a thickness of salt up to 1,000 m.
(b) Asse type salt masses partially penetrating overlying beds along fissure zone.
(c) Leine type broken anticline with salt squeezed up between the two flanks.
(d) Hannoverian type of true salt cores in which the salt may have a thickness of anything up to 3,000 m.

Considering now the true salt cores of Hannoverian type, there would appear to be two lines of development, uplift and penetration, according to the conditions under which the domes were formed.

In the first and best known type the tendency is for the uprising salt to lift the cover rocks, imparting to them a well-marked dome formation and causing them to suffer denudation. In this type of dome, therefore, we find under the unconformable post movement cover which may be Upper Cretaceous plus Tertiary or merely Tertiary, the salt core is surrounded by older beds—*i.e.*, Triassic dipping away from the salt and overlaid in turn by newer and newer formations. Naturally the simple structure outlined above is complicated in most instances by faults and unconformities, but the producing domes of Germany, Wietze, Nienhagen and Oberg are all more or less of this type, as is also the long belt of salt which runs from Lehrte south to near Hildesheim. Here one may see in the northern half higher Triassic beds dipping away on either side of the salt, but missing along the axis, while to the south they carry over the salt as an anticlinal arch.

There is, however, developed another type of dome which is more akin to the Gulf Coast domes and the diaper salt structures

[1] *Bull. Amer. Assoc. Petr. Geol.*, 1925, **9**, 1250.

of Rumania. This is the dome which has penetrated the cover rocks rather than raised them, so that the older rocks are not in this case brought near the surface. In such cases, for example, Sottorf, just south of Hamburg and Bedenbostel, 30 miles N.E. of Hanover, the contact rock at the upper edge of the dome is Upper Cretaceous.

Evidence from geophysical surveys is also accumulating to show that in the North German plain there are also deep-seated domes with a cover of 1500 m. or more; none of these has been drilled, so that, it is impossible to say anything with regard to their tectonic relations to the surrounding sediments. It is probable, nevertheless, that, when these are investigated, it will be found that they are of the penetrating type so far as they have risen with a slight arching of the unpenetrated beds above them. As would be expected, these two types are by no means sharply differentiated, and probably all the domes show both uplift and penetration, but there is a very marked difference at the two ends of the series. The probable causes for these two types will be dealt with later.

If any evidence in addition to the foregoing was required to show that the German true salt domes are merely the intruded Zechstein salt, it is amply given by the detailed study of the structure of the domes themselves which has been carried out wherever they have been exploited for potash. The internal structure of the domes is highly complex, but wherever they have been examined the stratigraphical succession can be correlated exactly with the undomed Permian salt, and the structures formed within the dome are exactly those which one would expect to be formed by flow structure. The potash beds, which are well known in the undomed salt series, are found within the domes contorted into all sorts of fantastic folding, but yet the stratigraphical succession can, in all cases, be made out.

The Mechanics of Salt Dome Formation.—The North German plain appears to give very definite evidence of this, and as many of the domes are so similar in their characteristics to those of other regions, it would appear only logical to argue from them to other salt dome regions.

The North German plain has in post Zechstein times been affected by tectonic movements and two lines stand out clearly:—

1. The Rhinish movement giving rise to roughly N–S lines.
2. The Saxon movement giving rise to WNW–ESE lines along the old Hercynian axes.

These movements, however, have not resulted in violent folding but have rather tended to develop intersecting series of faults and give rise to a structure which is, in the main, block faulting. There

is little acute folding apart from that in the immediate vicinity of the domes, the evidence is therefore against any very violent tangential forces having acted on the salt. There is, however, a distinct tendency for the formation of domes along these two tectonic lines, as has been pointed out by Stille[1], who makes the very interesting and important remark :—

"Certain zones of uplift can be traced from the peripheral areas far into the North German basin ; and with the advance into the latter along one and the same line of uplift, the form of the anticline goes over more and more into the form of the salt stock."

This would appear to sum up almost the whole question and link up the progressive types of salt masses directly with the weight of overlying beds deposited over the salt. In other words, so long as the cover is not too thick the salt beds act normally and follow the folding of the beds above and below. With a thicker cover the salt becomes plastic and tends to flow from the areas of higher pressure to those of lower pressure, *i.e.*, from the deeper areas to the anticlinal crests giving the thickened salt anticlines. With increasing cover the plastic flow of the salt becomes more marked, itself accentuating the initial tectonic fold. As to whether this further upward movement of the salt causes uplift of the overlying beds or penetration is probably largely controlled by the thickness of the cover, the penetrating type being the ultimate form due to increasing weight of cover. While the weight of overburden would appear to be the really important factor in the formation of the North German domes, their detailed structure is undoubtedly profoundly modified by tectonic factors. Salt rendered plastic by pressure must seek relief along the line of least resistance, and the actual form that the intruded salt will take will depend largely on whether that line of least resistance is a fracture zone, an incipient fold, or the intersection of such lines. This view is not in accord with that of Stille, who attributes the formation of the salt domes to lateral pressure, and regards them as "the extreme case of inharmonious folding." To the writer, however, the almost complete absence of folding, so far as is known, between the domes appears a great difficulty in assuming that tangential forces have played the dominant part; it would rather appear that folding has been the guiding factor as regards distribution, but that weight of overburden has supplied the power.

An interesting question which naturally arises here is the depth necessary to produce doming. That this is very considerable is clearly shown in the southern part of the basin, since in Thuringia practically horizontal potash beds are being mined in the salt series

[1] *Bull. Amer. Assoc. Petr. Geol.*, 1925, **9**, 417.

at a depth of 1000 m. and these show no tendency towards doming, in spite of the fact that one must allow for considerable removal of cover rocks by denudation.

The Braunschweig area is interesting in this connection as apparently representing a sharp transition from the undomed to the domed salt. Just south-west of Konigslutter a beautiful structural dome has been drilled to about 1000 m. and the Zechstein salt proved to underlie it as a perfectly conformable series, while 11 km. to the west, just east of the City of Braunschweig, a typical salt dome has been proved. Here the stratigraphical evidence rather points to the salt having been under a cover of some 2000 m.—2500 m.

Could one determine the geological horizon at which the movement of the salt commenced, a very accurate estimate of the overburden could be made, but this is no easy matter. Taken generally the main movement of the salt would appear to belong to the period represented by the Lower Cretaceous–Upper Cretaceous unconformity, and this again would point to somewhere about 2000 m. Earlier movement of the salt has been argued from the unconformities lower in the succession, which have been proved around the domes. These, however, in many cases, appear to extend far beyond the possible influence of the dome and therefore are more probably due to normal uplift and denudation.

While the main movement of the salt appears to have been between Lower and Upper Cretaceous, the movement has often continued long after this period, and in certain cases is still probably slowly taking place.

Finally, there is the question of relation of domes to oil. Is it purely a question of concentration due to structure, or is there a closer genetic relationship between the salt and the oil? We may set aside any question of purely inorganic origin, but there remain two possibilities for genetic relationship:—

1. That salt water associated with the domes played some part in the preservation and subsequent conversion of the organic material to oil.
2. That the earlier phases of the salt uplift gave rise to shallow water conditions which favoured a rich development of organisms and provided conditions suitable for their conversion to oil.

Both the above would mean that the formation of oil was localised around the domes and the second of the above possibilities was upheld strongly by the late Prof. J. Stoller.

There appear to be in Germany several well marked post Permian petroliferous horizons. The lowest of these is the Rhætic, then

come in ascending order the oilsands of the Lias, Dogger and Wealden. It is true that on the north side of Wietze oil is obtained from Senonian chalk, while shows of oil have been reported in many cases from Tertiary beds. There is, however, no very definite evidence of any post-Wealden formation of oil.

Now if the salt domes have had any influence on the formation of the oil, movement must have already taken place in Rhætic times, but this is unlikely; further, as we believe the main movement of the salt to have been post-Wealden pre-Senonian, we should, on the theory under discussion, certainly expect to find evidence of post-Wealden oil formation. While one cannot entirely rule out the possibility of some such tectonic relationships, it appears to the writer very much more probable that the formation of oil in Germany was, in the main, pre-doming, and therefore quite unconnected with the present system of domes, and that the domes have merely given rise to structures favourable for the concentration of oil in these petroliferous horizons. A certain parallel distribution of salt domes and oil might perhaps be due to both having some relation to the systems of movement. This has been intermittent and may have led to local conditions favourable to oil formation at different periods, while the distribution of the domes is certainly controlled in part by the same system.

To sum up, the evidence of Germany appears to point to the following:—

1. That salt domes are formed from normal sedimentary deposits of salt.
2. In the case of Germany the age is Upper Permian, but the salt of any other age would, under similar conditions, give rise to domes.
3. While lines of folding seem to determine the orientation of the domes and no doubt initiates them, the major movement seems to be due to the overburden rendering the salt plastic causing it to flow along the line of least resistance.
4. Such evidence as there is, rather points to an overburden of some 2000 m. being required before true doming takes place, and further that the greater the overburden the more the dome tends to penetrate rather than lift the overlying beds.
5. The function which salt domes play as regards oil appears to be the purely structural one of concentration.

Salt—Some Depositional and Deformational Problems.*

By G. M. Lees, M.C., D.F.C., Ph.D., F.R.G.S., F.G.S.
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1. The Conditions of Deposition of Saline Formations.

The Near East is particularly rich in saline formations of widely separated geological ages. In Persia and Iraq there is an extensive gypsum salt series, the so-called Lower Fars, of Miocene age, and in Persia there is also a much older salt group, the Cambrian Hormuz Series. Massive gypsum beds are also developed locally in the Eocene, the Cretaceous, the Jurassic and in the Triassic. In India there is an Eocene and a Cambrian saline formation. In Palestine gypsum beds are present in the Pliocene and Miocene. The salt dome of Jebel Usdum is of pre-Pliocene age and there is the present day Dead Sea with its deposits. In Egypt the Miocene contains thick salt and gypsum beds, and towards the Southern end of the Red Sea there is a group of salt domes, possibly of Triassic age.

Such gypsum and salt formations are usually classed as lagoonal deposits, but nowhere among the many lagoonal areas of the world to-day can we find conditions at all comparable with those under which most of these formations were formed. The most extensive salt depositing bodies of water of the present are inland lakes, such as the Dead Sea and Qara Bughaz. Marine saline lagoons are in all cases marginal to large bodies of normal sea, such as the Red Sea or the Gulf of Mexico.

Let us study the details of the Lower Fars of Persia and Iraq. This formation, where typically developed, extends from the Persian Gulf to and beyond the Iraq-Turkish border, a distance of about 800 miles. The breadth is about 150 miles.

The Lower Fars is, on an average, about 3000 ft. in thickness. It may be subdivided into stages, a basal stage with anhydrite, salt, grey marls and occasional foraminiferal or oolitic limestones and an upper stage of anhydrite, red and grey marls and limestones, but with little or no salt. The Lower Fars is underlain by the Asmari limestone of Lower Miocene to Oligocene age, and in some areas a transition series of anhydrite and limestone separates the two. It is overlain by the Middle Fars, a group of limestones, marls, sandstones and some gypsum. The zone of greatest thickness of the Lower Fars, which is likewise the zone with greatest development of salt and anhydrite in proportion to shale and limestone, extends

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through the centre of the foothill belt. Towards both the south-west and north-east the formation thins and first the salt and then the gypsum beds die out. The limestones and marls of the Lower Fars have a greater lateral extent than the gypsum.

If the Lower Fars Gulf was at all comparable with the present day Red Sea or Persian Gulf we should expect to find the greatest development of salt and gypsum in the marginal zones and marine deposits in the central zone ; but the reverse is the case. Individual gypsum beds have been followed for 70 miles and are probably more extensive.

A further difficulty in our understanding of the conditions of deposition of such salt-gypsum formations is presented by anhydrite. In general, at surface outcrop the calcium sulphate is in the hydrated form, but at depth anhydrite is more common. In what form was the sulphate originally deposited ? If it was formed as gypsum, we must assume that under moderate temperature-pressure conditions it is possible for the water to be expelled to form the anhydrous mineral, and later, when the bed is brought nearer the surface under the influence of circulating waters, it reverts to gypsum. The alternative is that the anhydrite was deposited as such.

On examining either possibility we meet with objections. We know that under experimental conditions the dehydration of gypsum can take place in a current of dry air at the moderate temperature of 70° C.[1] but under conditions of nature other factors are involved. The change from gypsum to anhydrite involves a theoretical shrinkage to 62 per cent., provided that the replaced water may escape immediately, but at the instant of change of any given molecule, it seems unlikely that the water can be eliminated, in which case the change involves an expansion. The change from gypsum to anhydrite and water would cause an increase of volume of 13 per cent. For this reason, it would appear that the effect of pressure would be to prevent the dehydration of gypsum, while a rise of temperature would tend to promote the change. In the case of a buried deposit we have no means of determining whether temperature or pressure is the dominant factor and we are forced to rely on observational evidence for information. For a more detailed discussion on this question reference is made to R. C. Wallace.[2]

In Persia from the surface to a depth of 300 to 500 ft. gypsum predominates in the Lower Fars, but below that depth anhydrite is the form with only inconsiderable amounts of gypsum. The general character of the anhydrite beds suggests that this is the original depositional form and that it has not been subject to the disturbance due to volume change which would have taken place

if the change from gypsum had occurred. Anhydrite is rarely met with at surface outcrop, but it is sometimes found. In some such occurrences of anhydrite the rock has a definite laminated texture, thin shale partings intercalated with the anhydrite representing presumably seasonal deposition. It is difficult to imagine that such a structure could be preserved if dehydration of original gypsum had taken place causing such a considerable volumetric change.[2] Similar laminated anhydrite, thought to indicate seasonal deposition, is known in many other lagoonal deposits as *e.g.*, in Texas, as described by Udden.[3]

Much research work remains to be done before we are in a position to postulate the conditions under which anhydrite is formed in nature. As far as the author's knowledge extends, there is no known case of formation of anhydrite at the present day, and in this instance the geological principle of examining present-day conditions to unravel processes of the past fails us. The classic experiments of Van 't Hoff and his pupils showed that with sea water over a temperature of 25° C. anhydrite is formed, below that temperature gypsum. With a saturated NaCl solution the limiting temperature is 30° C.

During the course of two journeys along the coasts of the Red Sea, one in winter and one in summer, and at various times around the Persian Gulf shores, the author has taken the opportunity of examining a large number of lagoons of various sizes and at various degrees of concentration. In all cases the calcium sulphate was being precipitated as gypsum in the form of arrow-head twin crystals, ranging in size from minute to about 2 in. in length. A single anhydrite crystal formed under natural conditions was never seen, an experience which agrees with that of many colleagues questioned on the subject.

In order to understand the conditions of deposition of the many salt-anhydrite formations we must, therefore, either postulate climatic conditions in the past very different from those which occur in the arid tropical zones of the present day, or that all anhydrite was originally gypsum, or that there was some governing factor of which we are not aware. Faunistic considerations render the first of these possibilities unlikely; the second does not accord with observational evidence as explained above, although admittedly the evidence is by no means conclusive, and so there remains the third.

In the case of the Lower Fars of Persia and Iraq it has been explained above how the greatest development of chemical depositions is located in the central zone, while limestones and marls have a greater lateral extent than gypsum. It is often assumed that such gypsum-salt deposits represent shallow water lagoons,

but this may not have been the case. The Lower Fars Gulf may have had a similar form to, although more extensive than, the present Persian Gulf. If the connection with the Indian Ocean were more restricted than at present the effect of tides and currents would be much reduced. Strong evaporation would take place at the surface, and a gradual concentration of the more saturated water in the central and deepest part of the Gulf would take place. The Dead Sea affords a striking example of how a gradual increase of concentration with depth can occur :—

Surface water—Dead Sea	19·2%	Salinity
20 metres depth	20·7%	„
42 „ „	24·3%	„
120 „ „	24·6%	„
200 „ „	25·1%	„
300 „ „	26·0%	„

It is not known whether or to what extent the freshness of the upper layers is due to the incoming river water spreading out over the surface of the sea or whether in some way gravity may be operative in the formation of this stratification of the water.

The surface waters of the Lower Fars Gulf may in a similar way have had a composition approaching that of normal sea water, while solutions sufficiently concentrated for precipitation of gypsum collected at depth.

During periods of greater evaporation or of less inflow the concentration in the central and deepest parts would become sufficient for the precipitation of salt, while only gypsum was formed at shallower depths. In this way it would be possible to explain the formation of limestones in the marginal zones, then a zone of gypsum and a central zone of gypsum and salt from the same body of water.

Regarding the gypsum-anhydrite problem, if a deep gulf is postulated the precipitation would take place under a pressure due to the column of water, a condition which is absent in shallow lagoons. The temperature at the bottom of such a lagoon is, however, an unknown factor. The author offers discussion on a speculative possibility that the less concentrated surface layers might transmit the short wave length heat rays of the sun to the lower layers and then prevent the escape of long wave heat radiation from these layers. An analogy might be made with the functioning of a greenhouse. Such a condition is known in some cases of inland lakes, and it might possibly apply to a certain extent to a marine gulf. It requires, of course, that convection currents should be reduced to a minimum. Grabau[4] quotes the following example of such abnormal temperature conditions: "Kaleczinzky, in his studies of the Hungarian salt lakes, found that while the surface water of the lake, which was

essentially fresh, had a temperature of 21° C. (69·8° F.), the brine at a depth of 72 cm., which had a salinity of 240 per mille, had a temperature of 56° C. (132·8° F.), while elsewhere temperatures of 70° C. or over (158° F.) were recorded for the deeper lying brines of salt lakes."

2. Salt Domes of Persia.

Southern and South-western Persia has two salt series—widely separated in age. The salt formation which is responsible for the many salt domes of Southern Persia, the so-called Hormuz series, is of Cambrian age, and the higher salt series is the Lower Fars. The latter has only formed one salt dome where the salt outcrops at the surface at Ambal on the Karun river, but many Lower Fars salt accumulations have been proved by wells drilled in the oilfields belt.

The salt domes of Southern Persia have been described in detail in a separate paper by Mr. J. V. Harrison. They have also been the subject of a series of earlier papers[6–10].

The Cambrian salt domes of Southern Persia are probably the most spectacular in the world. More than 100 of them are known. The average size is about three miles in diameter and in some cases they form mountains as much as 4000 ft. above the surrounding country. The preservation of such salt masses at the surface is only possible in an extremely arid region, such as this Gulf littoral, where the average yearly rainfall is about 2 in. Even with such a rainfall the solution of salt, though small in one year, must be a considerable factor when the thousands of years since the development of the principal physical features which we know at present. The salt dome of Kuh-i-Namak of Dashti (Kuh-i-Namak means Mountain of Salt) is the highest topographical feature of the district, and the inference is very strong that it is in a state of isostatic equilibrium—that the salt plug rises to compensate for erosion from its surface. A similar state has been suggested by Gignoux[11] to explain analogous circumstances in the case of some of the Algerian salt domes.

A number of examples of the Persian Salt domes are discussed in a later section dealing with the mechanism of salt movement.

3. The Tectonics of the Lower Fars of Persia.

The Lower Fars of Persia may be divided in general into three stages, the lowest of which, Stage I., contains the greatest development of salt. The Lower Fars lies between the rigid Asmari limestone below and the comparatively competent Middle and Upper Fars and Bakhtiari formations above. The saline beds behave like a lubricant and are responsible for the sliding of these higher rocks over the lower, causing an extreme structural discordance between the higher formations and the underlying Asmari

limestone. The Asmari limestone is the oil-reservoir rock, and the principal task of the geologist is the detection of suitable covered structures in this formation. In a country of almost perfect exposures this should have presented no serious difficulties if the surface structure conformed with that of the underground; but by reason of the incompetence of the Lower Fars such is not the case.

The oilfield of Masjid-i-Sulaiman is a striking example of the strong structural disconformity between the intense surface folding of the Lower Fars and the broad simple anticline in the Asmari limestone. The greatest accumulations of salt and anhydrite occur both on the steep south-west flank and on the gentle north-east flank of the limestone structure, while in the crestal region salt is subsidiary in amount or lacking. On the south-west flank the Lower Fars has been thrust over the axis of the adjacent Tembi syncline and on the north-east flank thrusts are locally developed towards the north-east. This is the Omega structure of Busk.

It is very difficult to estimate the original thickness of the Lower Fars in this region. At Asmari Mountain, where the whole series outcrops, no reliable measurement of thickness is possible on account of violent contortions and faulting. The hydration of anhydrite and the leaching out of the salt at the surface add further complications. At Masjid-i-Sulaiman a well on the north-east or gentle flank of the structure commenced in the basal group of the Lower Fars and drilled to 5822 ft. without reaching the limestone. This great thickness is partly the result of a packing together of the Lower Fars and probably partly due to accumulation of salt. On the south-west flank a well was drilled to 3,735 ft. in the Lower Fars and about half of this thickness was rock salt. Towards the north-west the limestone structure pitches under what is essentially a synclinal area, the Turkidiz syncline, with only a gentle subsidiary anticline in Upper Fars to mark the position of the Asmari limestone fold below. Two steeply folded zones of Lower Fars which surround this syncline apparently do not represent any structure in the limestone below. The Lower Fars at this north-west pitching end of the structure averages only about 500 ft. in thickness.

The mechanism of the thrust sheets of gypsum is by no means clear, and it is impossible within the scope of this paper to marshal adequately all the available evidence. Many of these thrust sheets are of young age, some even subsequent to the formation of the present topography. The argument has been advanced that these gypsum sheets represent material which has been squeezed out from below the adjacent deep synclines, the actuating force being the weight of these synclines. The problem is, however,

not so simple, as the weight of the syncline is counterbalanced by the vertical column of Lower Fars rocks on the limb of the anticline and, where there is no great topographic difference in height between syncline and anticline, the only force operative in this way would be the amount due to the difference in specific gravity between the rocks of the synclines and the Lower Fars. This difference cannot be great, and is unlikely to be sufficient to cause these extensive gypsum sheets.

A further and important factor is the hydration of anhydrite. Below a depth of 300 to 500 ft. the calcium sulphate is in the form of anhydrite, and above that depth in the form of gypsum. The hydration is obviously the effect of ground waters. The change from anhydrite to gypsum causes an increase in volume of 62 per cent., and the force caused by this expansion will act in all directions. It will partly cause a general bulging up of the area as a whole, partly it will find relief in intra-formational folding, and partly it may be a factor in the formation of these gypsum thrust sheets.

4. Palestine—Jebel Usdum.

The Jordan valley—Dead Sea Rift valley—was formed by a series of movements which took place during the Miocene and Pliocene epochs. During the Pleistocene the valley had acquired a relatively stable condition, and the diluvial deposits laid down during a period when the Dead Sea surface level was about 500 ft. above the present level have suffered practically no further movement. They form flat, regular terraces, locally considerably dissected by erosion, sloping gently towards the centre of the valley.

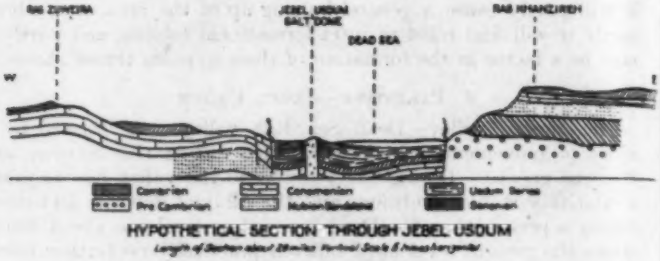
Only in two places throughout the length of the valley have these diluvial beds suffered any dislocation—namely, at Qarn-al-Ahmar and at Jebel Usdum. In both cases the disturbance is due to intrusive bodies which have formed elongated domal structures in the Pliocene to Miocene deposits underlying the diluvial beds. The latter have also been affected by the movement, although to a lesser degree. At Jebel Usdum the diluvium has been elevated to a height of several hundred feet above its normal level in the surrounding country. The intrusive body at Qarn-al-Ahmar is basalt and at Jebel Usdum it is salt.

Jebel Usdum (*i.e.*, Mount Sodom) is situated at the south-west corner of the Dead Sea. It is six miles in length by an average of one mile in breadth, and the highest point is about 720 ft. above Dead Sea level. The core of the mountain is massive rock salt, showing the banded structure so characteristic of most salt domes.*

*The intrusive nature of Jebel Usdum salt was first recognised by Messrs. B. K. N. Wyllie, K. A. Campbell and the writer in 1922. It had previously been regarded as an old Dead Sea deposit.

The top of the mountain has been eroded to a plateau and is covered by the diluvial deposits.

Salt outcrops along the greater part of the cliffs on the eastern side and in places also on the western flank of the mountain. A series, the Jebel Usdum series, of sands and shales, with gypseous marls and gypsum in the upper part, dip steeply off the margin of the salt. Their exact age is uncertain, but, by comparison with the Jordan valley at Melhamiya and elsewhere, they seem to be of Pliocene and perhaps Upper Miocene age. About 1000 ft. are exposed. The lowest beds found are shales with plant remains and some fresh-water fish which Sir Arthur Smith Woodward states belong to the Mugil family and may be of any age from Eocene onwards.



HYPOTHETICAL SECTION THROUGH JEBEL USDUM

FIG. 1.

Direct evidence of the age of the Jebel Usdum salt is lacking. The salt intrudes in the Jebel Usdum series and is therefore older in age than any of the exposed rocks. Also, as the lowest beds exposed are of fresh or brackish water character, it would appear that the salt is foreign to the series. On the opposite coast of the sea the Usdum series outcrops at Ed Draa, east of the Lisan, where it rests unconformably on the Upper Cretaceous. Neither salt nor gypsum are present in this area.

The complete stratigraphical sequence of the region from pre-Cambrian to Cretaceous is well exposed in the cliffs bordering the Dead Sea opposite to Jebel Usdum and only seven miles distant. (Fig. 1). There are some dolomites in the Cambrian and locally a thin gypsum bed in the Cenomanian, and this formation thins rapidly from west to east but otherwise no indication of a saline formation to which the Usdum salt might be attributed. On the other hand it is known that shorelines of both Jurassic and Triassic age must be close to Jebel Usdum, that is, that the marine transgressions of these ages reached their easterly limit in this zone.

(Fig. 2). At the north-eastern corner of the Dead Sea, the Upper Triassic beds are partly marine and partly contain a brackish water

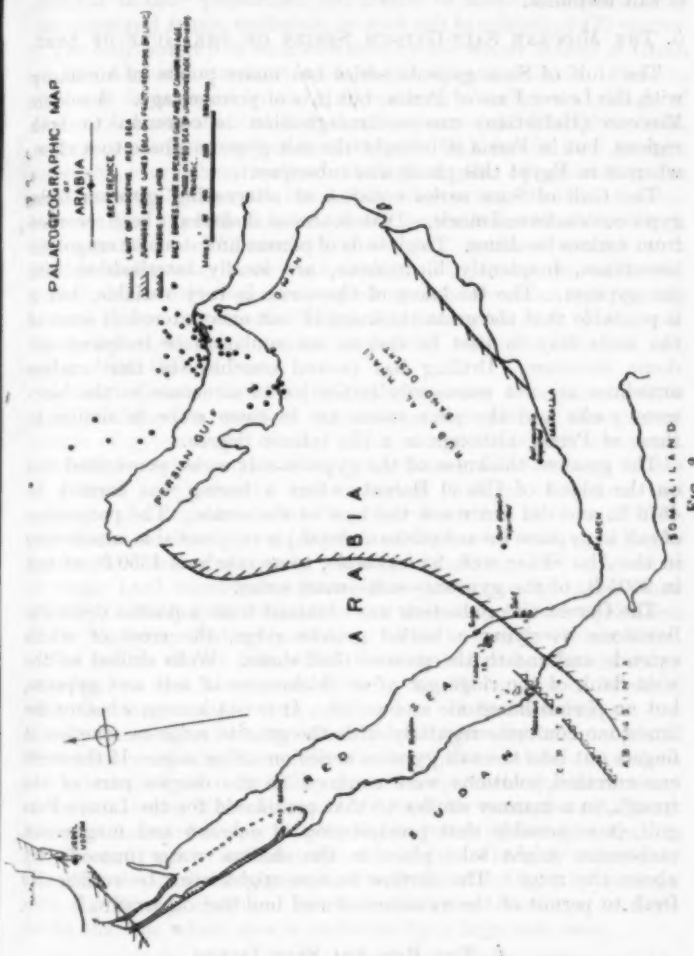


FIG 2.

fauna and from general considerations of palaeogeography we know that these ancient shorelines had a direction in general parallel to the present day Mediterranean coast.[10]

The question of the mechanism of the uprise of the Jebel Usdum salt will be discussed later in connection with the general problem of salt tectonics.

5. The Miocene Salt-Gypsum Series of the Gulf of Suez.

The Gulf of Suez gypsum series has many points of similarity with the Lower Fars of Persia, but it is of younger age. A middle Miocene (Helvetian) marine transgression is common to both regions, but in Persia it brought the salt gypsum phase to a close, whereas in Egypt this phase was subsequent.

The Gulf of Suez series consists of alternating gypsum beds, gypseous shales and marls. Diatomaceous shales have been recorded from various localities. Thick beds of porous limestone or aragonitic limestones, frequently bituminous, are locally interbedded with the gypsum. The thickness of the series is very variable, but it is probable that the great thickness of salt encountered in some of the wells may in part be due to accumulation or incipient salt dome structure. Drilling has proved conclusively that surface anticlines are not necessarily indicative of structure in the basement rocks and the phenomena are in some respects similar to those of Persia, although in a less intense degree.

The greatest thickness of the gypsum-salt series penetrated was on the island of Um el Hamet, where a boring was carried to 4670 ft. and did not reach the base of the series. The proportion of salt to gypsum (or anhydrite at depth) is very variable, amounting in the Abu Shaar well, for example, to as much as 1350 ft. of salt in 3505 ft. of the gypsum—salt—marl series.

The Gemsa oil production was obtained from a porous dolomitic limestone overlying a buried granite ridge, the crest of which extends underneath the present Gulf shore. Wells drilled on the west flank of the ridge got great thicknesses of salt and gypsum, but no porous limestone and no oil. It is not known whether the limestone conforms regularly with the granite ridge or whether it fingers out into the salt gypsum series on either side. If the more concentrated solutions were confined to the deeper part of the trough, in a manner similar to that postulated for the Lower Fars gulf, it is possible that precipitation of calcium and magnesium carbonates might take place in the shallow water immediately above the ridge. The surface waters might even be sufficiently fresh to permit of the existence of reef building organisms.

6. The Red Sea Salt Domes.

A number of recurrences of massive rock salt are known on the east coast of the Red Sea between latitudes 15° and 17° N. Salt outcrops are mined at Salif, Loheaja, Jebel Guma and Gizan

and the structure of a number of the Farsan Islands can only be explained by assuming buried intrusive salt bodies. A bore hole on Zifaf Island[13] penetrated 120 metres of coral limestone, marly limestone and marls, underlain by rock salt to a depth of 470 metres.

The only outcrop of rock salt seen by the writer is that of Gizan on the Arabian mainland east of the Farsan Islands. Massive rock salt is quarried in an open working close to the village of Gizan. A depth of about 40 ft. has been exposed. The salt is hard, massive and of crystalline texture with dark bands at 3 to 6 in. intervals, everywhere inclined at high angles. Surrounding the exposure on all sides are small hills of gypsum, shales and sandstones. The gypsum is mostly finely laminated with red or black shaley partings. The sandstones are grey, green or reddish, thin bedded and mostly somewhat shaley. The shales are well compacted and mostly fissile, in part somewhat calcareous and tending toward shaley limestones. There is a noticeable lack of the soft incoherent marls such as are associated with the Miocene salt series of the Gulf of Suez.

A short distance south of the salt exposure some considerable sized blocks of a massive sandstone occur among the general jumble of gypsum and shales. This sandstone is well cemented, brownish in colour and medium to coarse grained. Large blocks of a hard conglomerate with rounded boulders of quartz and quartzite and angular pieces of a yellow sandstone were found here, also blocks of a hard brown ferruginous limestone with some sandy patches and traces of poorly preserved bryozoa. The appearance of these hard sandstones strongly suggests an age older than Tertiary. Macfadyen considers that they may be the equivalent of the Egyptian Nubian sandstone which is mainly Cretaceous.

The jumble of low hills which form the Gizan headland occupy an elliptical area about two miles in length by one in breadth, with the longer axis north-north-west. It is bounded on one side by the sea and on the other sides by the flat alluvial plain. The rocks composing these hills are the gypsum—shale—sandstone series described above and they present a spectacle typical of many of the salt domes of the Persian Gulf, such for example as Al Buza. It is a confusion of steeply dipping blocks, many of them of enormous size, brought up by an intrusive salt body. The only outcrop of salt is in the artificial exposure already described but, by analogy with the Persian Gulf and other similar cases, there can be little doubt that the whole area is underlain by a large salt mass.

The Age of the Red Sea Salt.—There is no direct evidence of the age of the Red Sea salt. It has been considered by Macfadyen to be of Miocene age and therefore to be correlated with the Gulf of Suez salt series. When the regional palaeogeographic

conditions are studied, however, an older age for the salt seems more probable, especially as the Gizan salt has brought up with it masses of rock probably of pre-Tertiary age.

Our present knowledge of palaeogeographic conditions is depicted on the accompanying map (Fig. 2). The Miocene gulf extended at least as far south as Ras Benas, but it is unknown how much further south it may have reached in the central part of the Red Sea. At any rate, no Miocene is known on either coast line throughout the length of the Red Sea south of Ras Benas. Along the Sudan coastal region Plio-Pleistocene deposits rest directly on old crystalline rocks.

In Abyssinia and Eritrea it is possible to trace the northerly limits of the Triassic and Jurassic transgressions, and we find that the shore lines of these ages had a north-east–south-west trend. The stratigraphy of Abyssinia is as follows :—

Upper Cretaceous (?)	..	Lavas and tuffs.
Lower Cretaceous	..	Massive sandstone and conglomerates. Marls and limestones in Somaliland.
Jurassic	..	Antalo series. Limestones, dolomitic limestones and marls, locally somewhat gypseous. Bajocian to Kimmeridgian in age. Thickness, 1,500 to 2,000 feet.
Triassic. Adigrat series		(Exact age uncertain). Massive sandstones and red shales, limestones and dolomites with gypsum. Thickness up to 750 feet.
Pre-Cambrian ..	..	Crystalline rocks.

The Adigrat series appears to be the most probable formation which could be developed as a salt-bearing series. In the coastal area of Dancalia immediately opposite the Farsan Islands, Vinassy de Regny[13] found variegated red and green gypseous shales and sandstones which he compared lithologically with the Werfener series of the Eastern Alps.

The direction of the old shore lines was N.E.–S.W. and it may, therefore, be supposed that a similar stratigraphical sequence underlies the Farsan Islands and the Asir coast. The balance of evidence supports the view that the salt of this region belongs to the Adigrat series and is of Triassic age.

Blanckenhorn [14] records a salt deposit at Safir, east of Mareb on the Yemen high plateau, but nothing is known of its geological relationship. A mountain of salt in the hinterland of Makalla was reported to Little, but he was unable to visit it[15], and as the only gypsum formation which he has seen was the Miocene he considers the salt is probably of that age.

The palaeogeographic map shows the relative positions of the Persian Gulf and of the Red Sea salt domes. The former have been proved to be of Cambrian age and the latter are by inference

Triassic. The possibility that the Cambrian salt series extended through the unexplored Ruba al Khali to the Red Sea must be kept in mind but with our present knowledge, or rather lack of knowledge, it seems improbable.

7. Plasticity of Salt.

The recognition of salt dome structures as due to the independent movement of the salt in a plastic condition resulted in an intensive laboratory research work whereby the processes of nature might be imitated and investigated in miniature. By using graded materials ranging from rigid to fluid Escher and Kuenen [16] and Link [17] and others have demonstrated how diapir structures may be formed under a variety of conditions of vertical loading.

Fig. 3.

KUH-I-NAMAK (DASHTI).

a, Mio-Pliocene Series; b, Eocene Limestone; c, Peaks of d protruding through Salt; d, Cretaceous Limestone; e, Alluvial Plain; g, Salt mass.

Fig. 4.

KUH-I-ANGURU.

a, Scarp of Miocene Limestone; b, Scarp of Oligocene and Eocene Limestone; c, Peaks of b protruding through Salt; d, Hippuritic Limestone; e, Alluvial Plain; g, Salt mass.

Experimental work in connection with the plasticity of salt is less satisfactory when the results are applied to practical problems. In such experiments the importance of the time factor has not been considered sufficiently. Tests maintained through hours or even days are not comparable with geological processes dealing in years or many thousands of years.

Various methods have been employed. Geller [18] used a press apparatus from which the plastic material is forced through an aperture. Van Tuyl [19] used a method of drilling a hole in the salt and noting when a wire in the hole seized. Joffé and his colleagues

investigated the effect of pressure on the Laue diagram of a rock-salt crystal and noted the reading when the single points of the diagram were elongated into bands. They did not produce any visible distortion of the crystal, but the fact that the Laue diagram underwent distortion proves that internal movement within the crystal had already taken place [20].

In the following table the minimum pressures at various temperatures necessary to produce movement in rock salt obtained by Joffé are contrasted with those by Geller :—

	Joffé.	Geller.
20° C. ..	90 Kg/cm² ..	7800 Kg/cm²
60° C. ..	80 Kg/cm² ..	6800 Kg/cm²
100° C. ..	65 Kg/cm² ..	6125 Kg/cm²
200° C. ..	45 Kg/cm² ..	4500 Kg/cm²
250° C. ..	40 Kg/cm² ..	3900 Kg/cm²
300° C. ..	33 Kg/cm² ..	3300 Kg/cm²

Rock salt acquires an exceptionally plastic condition when wetted or when immersed in water. In hot water, not a brine, a salt crystal may be bent with the fingers. [21–22] The importance of this factor in nature must be borne in mind. Although the effect ceases with a brine, if circulating water not fully saturated came in contact with the margin of a salt dome the degree of plasticity of the salt would be radically altered.

The Persian salt domes present some unique evidence on the plasticity problem. In the case of several of the higher domes the salt has commenced to *flow* downhill as a salt-glacier. The rock remains solid with its normal banded structure and this form of glacier is distinct from a slide of debris and loose material which in other cases does occur. The only force acting on the salt to produce flow is due to the head of salt higher up the hillside, which in the case of Kuh-i-Namak (Dashti) is not more than 2,500 feet and probably considerably less. The author has not allowed for possible erosion from the top of the salt dome as he is forced to consider the salt to be in a state of isostatic equilibrium. The salt mountain is the highest topographical point in the country for a considerable radius and it is unreasonable to suppose that this could be maintained through a prolonged period of erosion if the salt were not gradually rising to compensate for solution. The average yearly rainfall here is about 3 ins., which although not excessive must reduce the soluble salt much more quickly than the surrounding limestones.

Assuming for the moment that the head of salt necessary to cause flowage is 2,500 ft., this represents a pressure of 170 Kg/cm². The average yearly temperature is about 30° C. so this pressure figure, itself based on a liberal estimate, corresponds much more closely with that of Joffé of 88 Kg/cm² than with the Geller figure of about 7600 Kg/cm².

Through the kindness of a colleague Monsieur H. G. Doll of the Société de Prospection Electrique, Paris, the author has received the following communication regarding the plasticity of the salt in the Alsace mines from Monsieur Crussard, Inspecteur Général des Mines, Conseiller Technique des Mines Dominiales :—

1. La déformation des galeries au sel par simple plasticité de celui-ci est certaine. Dans les cas les plus francs les choses se passent comme suit : A étant la galerie initiale, les bancs du toit fléchissent l'un après l'autre et donnent la forme B avec la cassure longitudinale caractéristique L. La purge du toit conduit peu à peu a la voûte ogivale. Au bout de *quelques mois*, le phénomène

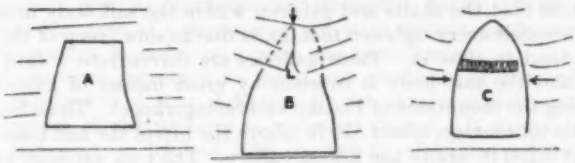


FIG. 5.

change. La pression se reporte sur les parois et tend à donner la forme C. Il faut alors raidir par des bois horizontaux que la charge casse *par compression*. Le passage de l'une des charges à l'autre est soudain, au point de donner l'illusion de deux causes distinctes. En réalité il s'agit simplement de la propagation lente de la déformation sur les quelques mètres qui séparent la clef de voûte des parois latérales de la galerie. L'ordre de vitesse de la propagation de la pression dans un cas comme celui d'un vide de galerie est donc celui du *mètre par mois*.

2. Influence de la profondeur. Les variations de profondeur des travaux sont assez faibles. Il est donc difficile de dire l'influence de la profondeur sur la tenue *des galeries*. Mais, au fond, je ne crois pas qu'elle soit importante et voici pourquoi. La masse qui est intéressée à la charge dans les galeries est un bloc schistes-sel qui, pendant longtemps (deuxtrois ans par ex) ne dépasse pas le plafond de sel compact situé à une trentaine de mètres au dessus de la formation potassique.

Il en est tout autrement dans les dépilages *lorsqu'ils sont suffisamment étendus* en largeur et longueur (mettons par exemple 300–500 mètres dans tous les sens). Alors le plafond de sel pèse, et l'influence de la profondeur apparait. Un exemple bien net de cela est la différence d'ensemble de tenue des toits de dépilage en moyenne dans les Mines Dominiales (profondeur 500 m.) et à St. Thérese (profondeur jusqu'à 1,000 m.). Dans les premières le toit est plus cassant, dans les secondes il est plus flexible, parceque la profondeur est plus grande et que la pesée d'ensemble est immédiate. Je rapproche cette constatation de l'apparition des dômes dans la partie profonde du bassin. Il y a ainsi comme un seuil de plasticité qui se place vers 700 mètres de profondeur, soit 159 Kg. au centimètre carré.

3. Dans les galeries il y a encore un autre phénomène assez caractéristique, c'est le glissement le long des feuillets minces d'anhydrite. Ces feuilles sont de véritables miroirs, de sorte que l'on a, avec les couches même modérément inclinées (10° par exemple) des phénomènes de charge de glissement comparables à ceux que donnent des terrains à 45° dans des couches ordinaires. On peut dire qu'à 10–15° on est deja en "dressant." C'est cela le rôle particulier de l'anhydrite. Je n'ai jamais rien constaté de sèrieux qui puisse être considéré comme un méfait dû à son hydratation.

J'ajoute pour mémoire que les phénomènes de plasticité et de charge sont bien plus marqués dans les horizons stratigraphiquement très différenciés (comme le sont les couches même de potasse et leurs alentours) que dans les horizons compacts comme le sel gemme massif. Si les galeries au sel gemme tiennent très bien, ce n'est pas parceque c'est du sel gemme, mais parcequ'elles sont en sel compact et homogène. Il en va tout autrement de l'espèce de jeu de cartes des terrains potassiques.

The importance of these observations is that M. Crussard considers that salt passes from a brittle to a plastic state at a pressure of about 150 Kg/sq. cm. For further information on the salt movements in these mines reference is made to Wood[21].

During a visit to Hallstatt Salt Mine some years ago the author was told that the shafts and galleries within the salt body must be re-excavated every eighteen months as due to slow creep of the salt they tend to close in. These galleries are driven into a steep hill side and the salt body is overlain by great masses of limestones forming the mountains of Platten and Solingerkogel. These heights are, on an average, about 810 ft. above the top of the salt mass and about 2,200 ft. above the lowest gallery. The rock pressure in the salt due to the weight of superincumbent beds will be about 70 Kg/cm^2 at its upper surface and about 160 Kg/cm^2 at the level of the lowest gallery.

The behaviour of the Hallstatt salt seems to provide further evidence to show that, given time, salt is capable of flowing when under only a small fraction of the pressure indicated by experimental results. The author is endeavouring to obtain more exact information regarding the amount and rate of the salt movement at Hallstatt, but at the time of writing has not yet had a reply to his queries. It would also be of great value if similar records could be obtained from other salt mines, although, of course, local conditions must always be kept in mind. If the salt mass is covered by an arch of rocks or by a series of blocks forming an arch with keystone, this structure would, perhaps, have sufficient strength to support part of its own weight.

8. The Mechanism of the Uprise of Salt Masses.

During a discussion on salt problems recently Mr. Romanes likened the uprise of a salt plug through hard rocks to driving a putty nail through a plank of wood. To explain that point of view, the action of a small jet of liquid in a 100 ton hydraulic jack is offered. An analogy may also be made with igneous dykes or stocks. A dyke of viscous lava may be injected through considerable thicknesses of normal rocks and the active pressure is exerted through this mobile sheet.

It would serve no purpose to review here the great controversy which has arisen, particularly in German literature, regarding the nature of the force which acting on the original bedded salt has produced the salt plug structures. The crystallisation theory of

Harris is now only of historic interest, and there remains the tangential pressure due to folding forces versus the vertical force due to weight of superincumbent rocks.

Much of the difficulty is due, in the author's opinion, to the assumption that a much greater force is necessary to render salt plastic than is actually the case. Fulda,[24] for example, has assumed that a thickness of overlying sediments of about 11,000 ft. is necessary before the salt becomes capable of flowing, after which a large but incalculable force must be available in order to drive the salt in plug form through its cover rocks and to overcome the resistance due to their normal strength. Some authors have assumed a state of compression, others of tension producing lines of dislocation in order to explain the phenomena.

If the force necessary to make salt plastic is of the order of one hundredth of that indicated by laboratory experiments, our conception of the problem is radically altered. It means that a salt bed under a load of 1000 to 2000 ft. of higher sediments is already capable of flowage, and the deeper the burial the greater the force available to break through the cover rocks. Tangential forces acting during periods of folding movements will cause complex structures, as in the case of the Persian Lower Fars, but the uprise of salt as plugs is not necessarily connected with either a compressional or tensional state of the earth's crust.

The Cambrian Salt Plugs of Persia illustrate very clearly the independence of such structures to normal folds; also, how the age of the uprise of the salt is not always related to periods of folding. The domes are mostly associated with anticlines, but in many cases they are not located on the highest part of the structure, but rather on the pitching ends or on the flanks. Some are situated in synclines. In most cases the exposures around the periphery of the domes are almost perfect. Where the salt has burst through soft beds, such as the sandstones and marls of the Mio-Pliocene Series, these are steeply upturned around the margin of the salt. Where a massive limestone such as the Cretaceous is penetrated, the fracture is clean with little or no upturning of the beds. The domes are round to elliptical in outline, but in some cases, where they are related to normal faults, they are in dyke form.

The age of the salt-bearing Hormuz Series is Cambrian, but the upward movement of the salt took place through a long interval of time from the Upper Cretaceous to the present day. A number of plugs reached the surface during this period and formed islands in the sea, just as in the case of many of the Hormuz Series islands in the present-day Persian Gulf. Evidence of emergence of the salt series is afforded by conglomerates of Hormuz material interbedded with the normal sediments on the periphery of the salt

body, while in a very short distance in any direction from the salt such conglomerates are absent. Mr. G. M. Shaw found at Tang-i-Darizari conglomerates with Hormuz pebbles interbedded with beds containing large Upper Cretaceous *Inoceramus*, probably *I. Cripsi*. Other cases are known of Hormuz plugs having reached the surface in Eocene and Lower Miocene time. Further sedimentation amounting to many thousands of feet followed, and in most cases the salt has again risen at a later date and penetrated these beds. In one case, at Deh Nau, however, the Miocene beds have been deposited on and against the salt and Hormuz rocks, and they have suffered no subsequent dislocation. The salt must therefore have lost its motive power, probably due to the supply of salt in its original bedded position being exhausted. The deeply buried salt domes of Texas now being discovered may not have been able to rise higher for a similar reason.

The principal folding of this part of Persia took place in the Pliocene, particularly in the latter part. Some earlier movements may be presumed in the early Tertiary by the presence of conglomerates or of non-sequences, but in no case does the degree of folding amount to a detectable angular unconformity. The uprise of the salt in the Cretaceous and early Tertiary took place in what was essentially an unfolded region. The number of the domes known to have formed islands in the early Tertiary sea is small but it is possible that the salt had in many other cases commenced its upward journey, but had not yet reached the surface. The lack of any connection between the subsequent folds and many of the salt domes may indicate that the uprise of the salt had commenced prior to the principal folding.

The rise of salt has continued into recent times and may in some cases still be rising (*e.g.*, Kuh-i-Namak of Daahti). At Qishm Island the post-Pliocene terraces are strongly tilted at the margin of the salt, whereas elsewhere these terraces are almost or quite horizontal, being in age subsequent to the last strong folding movement of the region.

The maximum height to which a salt dome can rise was discussed by F. Rinne in 1925.[20] If the thickness and average specific gravity of the sedimentary series overlying the salt is known (Fig. 6) the greatest height of a salt plug may be calculated; or conversely if the latter figure is known the depth of the original salt bed may be found. If Sp. Gr.$_1$=the average Sp. Gr. of the cover rocks and Sp. Gr.$_2$=that of the salt, then—

$$h_2 = h_1 \left(\frac{\text{Sp. Gr.}_1}{\text{Sp. Gr.}_2} - 1 \right)$$

This formula may be applied to Persian conditions where both h_2 and h_1 are known and we have a sufficient knowledge of the

formations to assume the specific gravities. There are several salt domes which reach about 4000 ft. above the surrounding plain, *e.g.*, Kuh-i-Namak of Dashti and this appears to be the maximum height. The salt of these high domes must be slowly rising to compensate for erosion and to allow the salt to remain at a higher

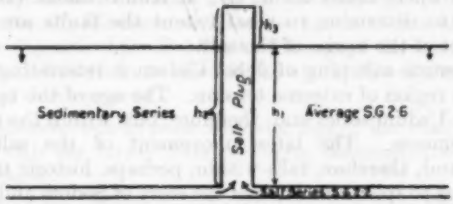


FIG. 6.

elevation than the surrounding limestones. The average Sp. Gr. of the stratigraphical sequence is about 2·6 and of the salt with its contained Hormuz blocks about 2·2, then

$$h_1 = \frac{h_2}{\left(\frac{\text{Sp. Gr.}_1}{\text{Sp. Gr.}_2} - 1\right)} = \frac{4000}{\left(\frac{2{\cdot}6}{2{\cdot}2} - 1\right)} = 22{,}000 \text{ ft.}$$

The average formation thicknesses for the region are as follows :—

	feet.
Pliocene and Miocene	7,000
Oligocene	600
Eocene	2,500
Cretaceous	5,000
Jurassic	1,500
Trias and Permo-Carboniferous	5,000
Devonian to Silurian ca.	1,000
Cambrian (above the salt) ca.	1,000
Total thickness	23,600

These thicknesses vary somewhat in different parts of the country (*vide* paper by Mr. J. V. Harrison) but the total thickness ranges between 20,000 and 30,000 ft. In the above calculation the Sp. Gr.'s are not exact figures but by varying them within possible limits the figure for h_1 remains between 20,000 and 30,000 ft.

Various attempts have been made to align the Persian salt plugs along lines of dislocation but in vain. The plugs are so numerous that lines may be drawn through them in almost any direction, but no regular system can be discerned. Moreover, what are lines of dislocation as the term is commonly applied to explain salt dome difficulties ? Many of the Persian domes have burst through their

cover rocks regardless of structure, and in spite of perfect exposures in general, neither dislocation nor fault is present by which to explain the location of the plug. In some cases where plugs are associated with faults, as at Kushk Kuh, they are definitely elongated along them and have the form of a dyke rather than a circular plug. In other cases where faults occur, *e.g.*, at Kuh-i-Namak (Dashti) it is impossible to determine to what extent the faults are the cause or the effect of the uprise of the salt.

The Palestine salt plug of Jebel Usdum is interesting in that it occurs in a region of extreme tension. The age of the uprise of the salt is post-Usdum series and, therefore, falls within the time of the Rift movements. The latest movement of the salt is post-Dilubium and, therefore, falls within, perhaps, historic time, and it is interesting to speculate whether the story of Sodom and Gomorrah may not have been in some way connected with the movement of the salt dome. The salt of Jebel Usdum has behaved in a similar way and produced a similar type of structure to the basalt intrusion of Qarn-al-Ahmar in the Jordan Valley.

The Red Sea salt domes also lie within a region of tension and the age of their uprise is Pliocene and Pleistocene. It is not possible with our present knowledge to connect these domes with any fault lines, as their distribution seems to be unrelated to any definite system. Part of the salt dome area is occupied by basaltic intrusions and volcanoes of Tertiary or Quaternary age.

9. Summary.

1. The conditions of deposition of various saline formations of the Near East are discussed. The Lower Fars of Persia is a series of gypsum, salt and marl, but there is reason to believe that it was laid down in an extensive and perhaps deep gulf and not in local shallow lagoons. Within 300 to 500 ft. of the surface the calcium sulphate is present as gypsum and below that depth as anhydrite. It is unlikely that the change from gypsum to anhydrite takes place in nature, and if anhydrite is the primary form, what are the conditions governing its formation? There is no known case of precipitation of anhydrite at the present day, even in arid tropical belts, so some factor such as pressure of water in a deep gulf or abnormally high temperature must have been operative.

2. The Persian salt formation is of Cambrian age. The domes have risen at various times from Upper Cretaceous to present day. Some seem now to be in a state of isostatic equilibrium, the salt slowly rising to compensate for erosion. Those salt plugs which rose in Upper Cretaceous and early Tertiary were prior to any important folding movement.

3. The Lower Fars of Persia, by reason of its incompetence, has reacted to folding movements very differently to the underlying Asmari limestone or overlying Middle and Upper Fars. Surface structures in many cases give little or no indication of the position of the underlying Asmari limestone folds.

4. The salt dome of Jebel Usdum in Palestine penetrates the Usdum series of Pliocene or Miocene age and has elevated the Pleistocene deposits of the Dead Sea. The age of the salt is unknown but the area is known to be close to the shore lines of the Cambrian, Triassic and Jurassic seas.

5. The Miocene salt-gypsum series of Egypt has many points of similarity with the Lower Fars of Persia, although the structures are less intense.

6. The Red Sea domes are allocated on and near the east coast between latitudes 15° and 17° N. The salt is possibly of Triassic age.

7. The plasticity of salt is discussed. Laboratory experiments lack the time factor and their results give pressures much in excess of those necessary in nature to make salt flow.

8. When a salt formation is buried to about 2000 ft. the pressure renders the salt plastic. When the formation is more deeply buried the extra pressure is available to force the plastic salt through and overcome the strength of the cover rocks. Tangential pressure is not necessary for the formation of salt domes. In the case of the majority of the Persian salt domes, in spite of excellent exposures, there are no visible lines of dislocation or major faulting which could account for the distribution of the plugs.

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Salt Domes of Texas and Louisiana Gulf Coast.

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S.B., F.G.S., F.G.S.A., F.A.G.S., M.A.A.P.G., etc. (Member).

Introduction.

The best-known salt dome region in either North or South America and one of the best known in the world is that of Texas and Louisiana, commonly known as the Gulf Coast District. The oil and gas fields formed about these domes constitute a petroliferous province quite distinct in geological character from fields situated to the north, north-west, west and south-west. For this reason the fields of northern Louisiana, southern Arkansas, Oklahoma, central, northern, western and south-western Texas and the State of Vera Cruz, Mexico, manifest in general little similarity to the Gulf Coast fields of the United States.

From the eastern-most recognised salt dome—Sorrento, just east of Mississippi River—to the south-western-most dome—probably Chapeño,[1] in Mexico, 30 miles south of the international boundary—the district is over 500 miles long; and, from the Gulf of Mexico to the northern-most domes in the vicinity of the Texas and Pacific railroad, the distance is 230 miles.

Two groups of salt domes are recognised in the Gulf Coast District. One of these, (*a*) in northern Texas and northern Louisiana, lies approximately 100 miles north of the nearest known dome of (*b*) the outer or "Coastal" group. Structures of the northern group are distinguished by the designation "interior domes," but both groups are considered as being within the "Gulf Coast District." None of the interior domes has produced commercial quantities of oil or gas until recently. The interior domes of Texas are discussed by Powers[2] and the interior domes of Louisiana by Spooner.[3] The coastal domes of both States are described in many papers, some of which are listed in footnotes of the present paper.

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[1] Ben C. Belt, "Chapeño Salt Dome, Tamaulipas, Mexico," Geology of Salt Dome Oil Fields, published by American Association of Petroleum Geologists, 1926, pp. 772–3.

[2] Sidney Powers, "Interior Salt Domes of Texas," *op. cit.*, pp. 209–68.

[3] W. C. Spooner, "Interior Salt Domes of Louisiana," *op. cit.*, pp. 269–344.

Discovery and Development.

The discoverer of petroleum on salt domes was Capt. A. F. Lucas, who in 1901 drilled a well at Spindletop, Jefferson County, Texas, opening up a famous field. As early as 1894 he had made diamond drill borings in rock salt to maximum depth of 2100 ft. at Jefferson Island, Louisiana, 2740 ft. at Belle Isle, and similar borings at Weeks Island and Anse la Butte had encountered pure rock salt masses of great depth. Writings by Lucas on this subject appeared from 1899 onwards[4]; and the existence of the domes was confirmed, soon after the Spindletop completion, by Hill,[5] who gives Lucas full credit for the discovery of petroleum on this type of structure.

An outstanding feature at Spindletop is the presence of a topographic dome rising 12 ft. above the surface of an otherwise flat plain and hardly discernible to the eye; yet the underlying structure is the identical type found at the "Five Islands"[6] (or, originally, the "South Islands")—where rock salt is mined in the adjoining State of Louisiana—these being the most conspicuous landmarks on the coast of the Gulf of Mexico in hundreds of miles.

Up to later than 1920 comparatively few salt domes had been discovered in the Gulf Coast District, out of which less than a score were commerically productive of oil or gas. Developments on this type of structure received an impetus about 1926 owing to the discovery that the domes could be located in most cases through the use of the seismograph and torsion balance; so that, with the aid of these instruments, the number of known domes was soon tripled. Some of the earliest discovered domes, productive or considered favourable as regards their "cap rock," were neglected for years, but were later redrilled and oil was discovered on the flanks.

Enumeration of Domes.

The list of known domes (Table I.), as proved by their outcrops or by drilling, has been brought as nearly up to date as possible through the help of the *Oil Weekly* and other recent literature.[7] The serial numbers used in this table refer to the positions of the respective domes on Fig. 1.

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[4] "Rock Salt in Louisiana," *Trans. Amer. Inst. Min. Engrs.*, 1899, **29**, 463; also *J. Ind. Eng. Chem.*, 1912, **4**, No. 2, and "The Dome Theory of the Coastal Plain," *Science*, N.S., 1912, **35**, 961–964.

[5] Robert T. Hill, *J. Franklin Inst.*, 1902, **154**, 143, 225 and 263.

[6] F. E. Vaughan, "The Five Islands, Louisiana," Geology of Salt Dome Oil Fields, pp. 356–97.

[7] Donald C. Barton, in Geophysical Prospecting, American Institute of Mining and Metallurgical Engineers, 1929, Table 4, pp. 618–9, and in *Bull. Amer. Assoc. Pet. Geol.*, 1930, **14**, Tables I. and II. pp. 1108–9.

Mineral Wells
Desdemona
Corsicana
Powell
Mexia
TEXAS
Thrall
Luling
GULF
Rio Grande
MEXICO

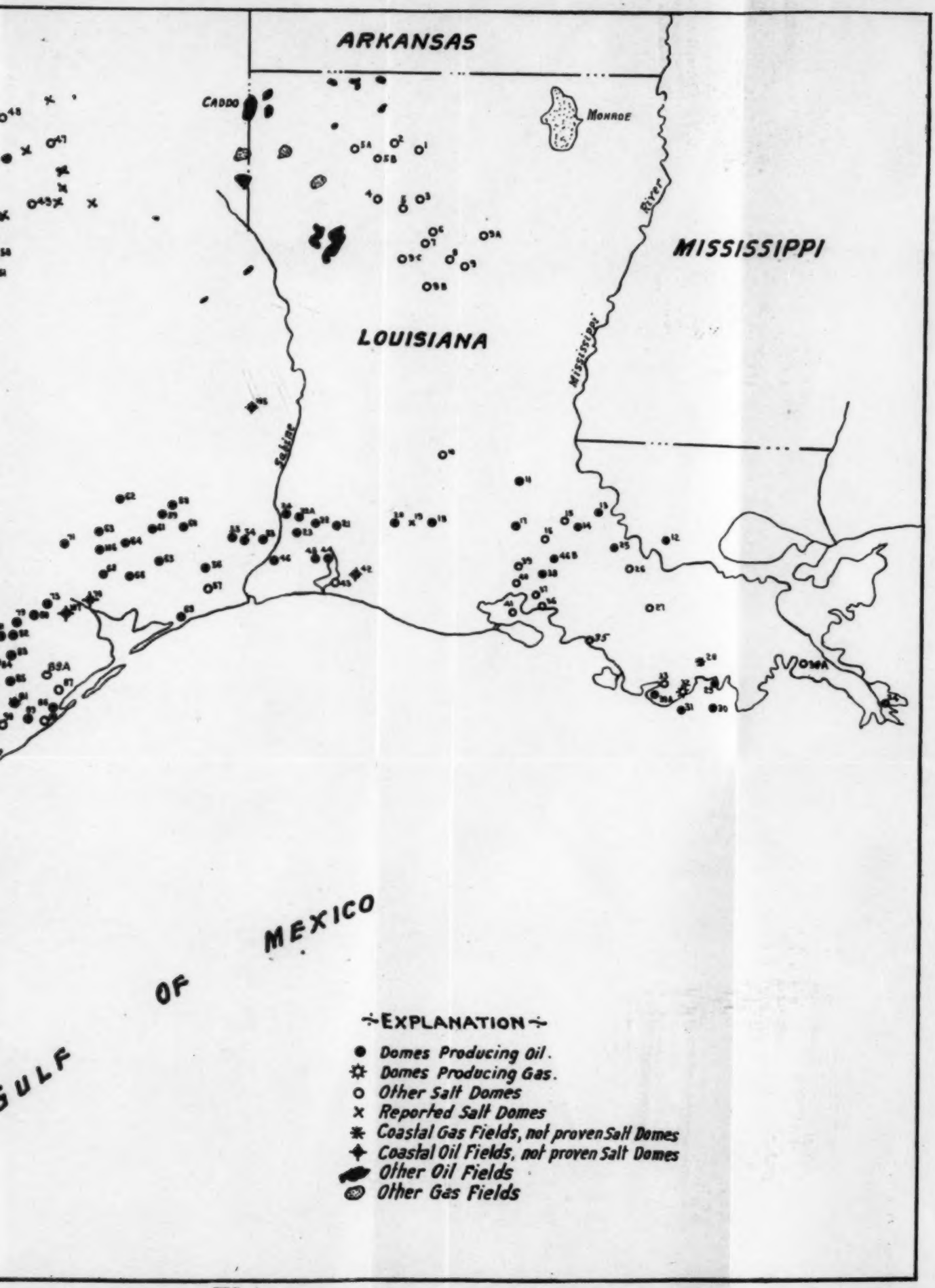

FIG. 1.
SALT DOMES OF TEXAS AND LOUISIANA.

TABLE I.

Results on Known Salt Domes and Other Coastal Fields.

No.	Name.	Parish (in Louisiana) or County (in Texas).	Product.
	Interior Salt Domes of Louisiana.		
1.	Arcadia	Bienville	Salt.
2.	Gibsland	„	„
3.	Rayburn	„	„
4.	Kings	„	„
5.	Prothro	„	„
5-A.	Bistineau	Webster	„
5-B.	Vacherie	Webster-Bienville	„
6.	Prices	Winn	„
7.	Drakes	Winn-Natchitoches	„
8.	Winnfield	Winn	„
9.	Cedar Creek	„	„
9-A.	Sikes	„	Anhydrite.
9-B.	Coochie Brake	„	Salt.
9-C.	Clear Lake	Red River	Salt and gas.
	Coastal Domes of Louisiana.		
10.	Pine Prairie[§]	Evangeline	Salt.
11.	Port Barre	St. Landry	Oil.
12.	Sorrento	Ascension	„
13.	Bayou Bleu	Iberville	„
14.	Bayou Bouillon[§]	St. Martin	„
15.	Bayou des Glaises	Iberville	Salt.
16.	Section 28[§]	St. Martin	„
17.	Anse la Butte	„	Oil.
18.	Jennings[§]	Acadia	„
19.	Roanoke	Jefferson Davis	
20.	Welsh†[§]	„ „	Oil.
21.	Lockport	Calcasieu	„
22.	Sulphur[§]	„	Sulphur and oil.
22-A.	Edgerly	„	Oil.
23.	Vinton	„	„
24.	Starks	„	„
25.	White Castle	Iberville	„
26.	Napoleonville	Assumption	Cap rock.
27.	Chacahoula (Lutcher or Thibodaux)	La Fourche	Salt.
28.	Houma[§]	Terrebonne	Gas.
29.	Lake Barre	„	Oil.
30.	Caillou Island	„	„
30-A.	Dog Lake	„	„
31.	Lake Pelto	„	„
32.	Bay St. Elaine	„	Gas and salt.
33.	Four Isle	„	Salt.
33-A.	East Bay Junop	„	Cap rock.
34.	Garden Island Bay	Plaquemines	Salt.
34-A.	Lake Grande Ecaille	„	„
35.	Belle Isle[§]	St. Mary	„
36.	Côte Blanche†	„	„
37.	Weeks Island[§]	Iberia	„
38.	New Iberia	„	Oil.
39.	Jefferson Island[§]	„	Salt.
40.	Avery Island[§]	„	„
41.	Vermilion Bay	„	„
42.	Sweet Lake[§]	Cameron	Oil.
43.	Calcasieu Lake	„	Salt.
44.	East Hackberry	„	Oil.

TABLE I—*continued*.

No.	Name.	Parish (in Louisiana) or County (in Texas).	Product.
45.	Hackberry	Cameron,	Oil.
46.	Black Bayou	"	"
46–B.	Fausse Point (Loreauville)	Iberia	"
	Interior Domes of Texas.		
47.	Steen	Smith	Salt.
48.	Grand Saline	Van Zandt	"
49.	Brooks	Smith	"
50.	Keechi	Leon	"
51.	Palestine	Anderson	"
52.	Butler	Freestone	"
52–A.	Hainesville[3]	Wood	
52–B.	Mt. Sylvan[3]	Smith	
52–C.	East Tyler[3]	"	
52–D.	White House[3]	"	
52–E.	Bullard[3]	"	
52–F.	Troup[3]	"	
52–G.	La Rue[3]	Henderson	
52–H.	Bethel[3]	Anderson	
52–I.	Cronin[3]	"	
52–J.	Oakwood[3]	Freestone	
52–K.	Van†[3]	Van Zandt	Oil.
	Coastal Domes of Texas.		
53.	Orange	Orange	Oil.
54.	Port Neches	"	"
55.	Spindletop	Jefferson	"
56.	Fannett	"	"
57.	Big Hill, Jefferson County[3]	"	Cap rock and non-commercial oil.
58.	Saratoga[3]	Hardin	Oil.
59.	Batson[3]	"	"
60.	Sour Lake	"	"
61.	Hull	Liberty	"
62.	Davis Hill	"	
63.	North Drayton	"	"
64.	South Liberty (South Dayton)	"	"
65.	Hankamer	"	"
66.	Moss Bluff	"	"
67.	Lost Lake	Chambers	"
68.	Barbers Hill[3]	"	"
69.	High Island	Galveston	"
70.	Goose Creek†[3]	Harris	"
71.	Humble	"	"
72.	Hockley[3]	"	"
73.	Pierce Junction	"	"
74.	Clay Creek	Washington	"
75.	Brenham	"	"
76.	Raccoon Bend	Austin	"
77.	Sans Felipe	Waller	"
78.	Orchard	Fort Bend	"
79.	Sugarland (Dewalt)	" "	"
80.	Blue Ridge[3]	" "	"
81.	Big Creek	Fort Bend	Oil.
82.	Long Point	" "	"
83.	Nash	" "	"

TABLE I—*continued.*

No.	Name.	Parish (in Louisiana) or County (in Texas).	Product.
84.	Damon Mound[§] ..	Brazoria	Oil.
85.	West Columbia ..	,, ...	,,
86.	Stratton Ridge ..	,, ...	Salt.
87.	Hoskins Mound ..	,, ...	Sulphur.
88.	Bryan Heights[§] ..	,, ...	,,
89.	Allen	,, ...	Oil.
89–A.	Danbury	,, ...	Salt and non-commercial oil.
90.	Hawkinsville	Matagorda	Salt.
91.	Clemens	Brazoria	,,
91–A.	Bloomington*.. ..	Victoria	Gas.
91–B.	Edna*	Jackson	,,
92.	Boling	Wharton	Oil and sulphur.
93.	Markham	Matagorda	Oil.
94.	Refugio*	Refugio	Gas and oil.
95.	White Point* ..	San Patricio	Gas.
96.	Pearson (Saxet)* ..	Nueces	,,
97.	Palangana[§]	Duval	Sulphur.
98.	Piedras Pintas[§] ..	,, ...	Oil.
99.	Kingsville*	Kleberg	Gas and oil.
100.	Falfurrias[§]	Brooks	Gas.
104.	Big Hill, Matagorda County[§]	Matagorda	Sulphur.
105.	Jasper*	Jasper	Non-commercial oil.
106.	Esperson	Liberty	Oil.
107.	Mykawa	Harris	,,
	Salt Dome of Northern Mexico.		
108.	Chapeño	State of Tamaulipas†	

* Not a salt dome.

† Not yet demonstrated to be a salt dome.

§ The domes enumerated below are described in the places mentioned in Geology of Salt Dome Oil Fields, *op. cit.* :—

10. Pine Prairie, by Donald C. Barton, pp. 419-36.
14. Bayou Bouillon, by David Donoghue, pp. 345–51.
16. Section 28, by David Donoghue, pp. 352–5.
18. Jennings, by Donald C. Barton and R. H. Goodrich, pp. 352–5.
20. Welsh, by Lyman C. Reed, pp. 437–51.
22. Sulphur, by P. K. Kelley, pp. 452–69.
22–A. Edgerly, by H. E. Minor, pp. 470–7.
35, 36, 37, 39 and 40. By F. E. Vaughan, pp. 356–97.
57. Big Hill, Jefferson County, by A. S. Henley, pp. 497–500.
58. Saratoga, by John R. Suman, pp. 501–23.
59. Batson, by George Sawtelle, pp. 524–9.
64. South Liberty, by W. F. Bowman, pp. 558–69.
68. Barbers Hill, by George M. Bevier, pp. 530–45 (and later by P. C. Murphy and Sidney A. Judson, *Bulletin Amer. Assoc. Petrol. Geologists*, 1930, 14, No. 6, pp. 719–41).
70. Goose Creek, by H. E. Minor, pp. 546–57.
72. Hockley, by Alexander Deussen and Laura Lee Lane, pp. 570–99.
80. Blue Ridge, by D. S. Hager and E. Stiles, pp. 600–612.
84. Damon Mound, by George M. Bevier, pp. 613–43.
86. Stratton Ridge, by P. L. Applin, pp. 644–77.
88. Bryan Heights, by William Kennedy, pp. 678–90.
97, 98 and 100. By Donald C. Barton, pp. 718–69.
104. Big Hill, Matagorda County, by A. G. Wolf, pp. 691–717.

§ Listed by Donald C. Barton, pp. 618–9 in "The Seismic Method of Mapping Geologic Structure," Geophysical Prospecting, published by Amer. Inst. Min. and Met. Engrs., pp. 572–624.

General Description.

If a proper structural classification of salt domes be into (*a*) "perforated domes or *diapir* structures" (*i.e.*, those in which the mass of salt and associated minerals penetrates all observed formations) and (*b*) "closed domes" (those in which the structures are simply domed over the crests of the underlying salt masses), one finds both types in the Gulf Coast District. Structurally and genetically their principal difference appears to be that the salt masses of the first class have forced their way through the sediments to the earth's surface, whereas those of the second class have stopped short of the surface or are still rising.

In exterior contour the Gulf Coast salt masses are usually boss-like to mushroom-shaped and range from a fraction of a mile to three or more miles long and up to a mile in greatest width; they are flat or rounded on top and the edges descend steeply and asymmetrically in all directions to undetermined depths. Although oil exists in the "cap rock" in many of the fields, it is more often held in "sands" that abut against the domal flanks. Where the salt mass is entered by shafts, as in mines at Avery Island, schist-like banding and intense folding of the light and darker layers of salt are evident. Usually the salt is remarkably pure.

For many years the wells drilled on salt domes were only moderately deep, but this class of fields has now entered the category of "deep production." At the beginning of 1930 the deepest oil found in the Gulf Coast came from a depth of 7447 ft. at Jennings, Acadia Parish, Louisiana. At least 17 of the Gulf Coast fields now derive their production from below 5000 ft.; for, early in 1930, the following-named Texas fields had taken their places in this class: Allen, Barbers Hill, Fannett, High Island, Hull, Humble, Moss Bluff, North Dayton, Orange, Pierce Junction, Refugio† and Spindletop. Fields obtaining production below 5000 ft. in southern Louisiana at the same date were Black Bayou, Jennings, Lockport, Sweet Lake† and Sulphur.

Stratigraphic Relationships.

The surface of southern Texas and southern Louisiana consists of Recent, Quaternary and Tertiary sediments, except in the perimeter of a few domes of the "interior" group, where the Upper Cretaceous or Gulf series appears throughout a small area. Beneath the "coastal" group of domes the Yegua formation of Eocene age is the oldest stratum definitely known, whereas in the "interior" group the Glen Rose formation of Lower Cretaceous or Comanchean age has been reached in one or more instances. The

† Not a salt dome field.

principal formations, known on the basis of outcrops or of data furnished by drilling, are listed in Table II.

TABLE II.

*Stratigraphic Column for Salt Dome Fields.**

(*Exclusive of the Salt.*)

System.	Series.	Group.		Formations.
Quaternary	Pleistocene and recent.			
UNCONFORMITY.				
Tertiary	Pliocene ..	Flemming		Qeynosa, Lagarto, Lapara, Citron, etc.
	UNCONFORMITY.			
	Miocene ..			Oakville, Pascagoula, etc.
UNCONFORMITY.				
	Oligocene ..	Catahoula		Hattiesburg and Catahoula.
	Eocene	Jackson		Manning. Shawnee. Frio. Diboll. Fayette.
		Claiborne group	Cockfield	Yegua. Nacogdoches. St. Maurice.
			Cooks Mtn.	Jonesboro. Crockette or Sparta. Mindan,
			Cane River or Mt. Selman ..	Weches. Queen City. Reklaw.
		UNCONFORMITY.		
		Wilcox†		Carrizo. Indio.
		Midway		

* As an attempt has been made here to correlate the respective nomenclatures of Texas and Louisiana (north and south), some inconsistencies may be expected in this generalized table. No stratigraphic column is representative for all of the salt dome fields.

† The Wilcox formation of the Gulf Coast is *not* the same as the "Wilcox sand" of Oklahoma drillers.

TABLE II.—*continued.*

System.	Series.	Group.	Formations.
Quaternary	Pleistocene and recent.		
UNCONFORMITY.			
Cretaceous	Gulf	Navarro	Arkadelphia clay. Nacatoch.
		Pecan Gap	Saratoga and Marlbrook.
		Taylor	Annona chalk. Ozan. Brownstone.
		Austin	Tokio.
		Eagle Ford	
		Woodbine	
	UNCONFORMITY.		
	Comanchean ..	Washita	Buda. Del Rio. Georgetown.
		Fredericksburg	Edwards. Comanche Peak. Walnut clay.
		Trinity	Glenrose. Sand. Travis Peak.

The salt and the minerals of the "cap-rock" accompanying it are excluded from the table. The sedimentary beds which produced the salt masses may lie 10,000 to 15,000 ft. below the surface, on the basis of German analogies.[10] In that country, where several types of salt domes exist, those that are stock-like (similar to Texas and Louisiana structures) are found in the central parts of the basin, where the original salt series is buried at great depth, whereas "salt anticlines" occur in shallower, border areas. Moreover, evidence of the magnitude of the upthrusts is found in East Texas itself; for Stephenson tells us[11] that "in the Palestine dome, in

[10] E. A. Wendlandt and G. M. Knabel (p. 1374) in "Lower Claiborne of East Texas, with Special Reference to Mount Sylvan Dome and Salt Movements," *Bull. Amer. Assoc. Petr. Geol.*, 1929, **13**, 1347–1375.

[11] L. W. Stephenson, "Structural Features of the Atlantic and Gulf Coastal Plain," *Bull. Geol. Soc. America*, 1928, **39**, 887–900.

Anderson County, Texas, a block of Buda limestone, the uppermost of the Comanche (Cretaceous) formations, was raised to the surface from it normal position, which is more than 5000 ft. below the surface, as shown by the record of a well near by."

Structural Relationships.

Since the Gulf Coast region is largely a comparatively flat plain, and since the superficial deposits are mostly of rather recent age, little is known of the underlying tectonics. Correlations by means of wells indicate that the sediments, dipping southward from the Arkansas and Oklahoma borders to the Gulf of Mexico and southeastwards from a line passing from north-east to south-west through central Texas, constitute a series thousands of feet in thickness, forming the north flank of a great basin that is largely buried beneath the Gulf.

The northern part of this basin has a few interruptions, such as the Caddo uplift of Louisiana and the Mexia and Techuacana fault systems[12] of central Texas, but nearer the Gulf the evidence of domes larger than salt domes is more rare. A few of the fields named in Table I. are, as indicated in a footnote, almost certainly not salt domes, and several others have not been drilled to the salt; but, in general, there is no doubt of their nature. Evidence that certain fields are really salt dome structures is cited by Miner[13]

In searching for tectonic relationships nothing of interest (with the single exception of the Sorrento dome) is fond on the immediate coast of the Gulf east of Mississippi River, and the flat plains stretch east across southern Mississippi and southern Alabama into northern Florida, a distance of over 300 miles. Structures that have been found farther north in Mississippi have nothing in the nature of salt domes; and, on the contrary, a gas field of a different type is found at Jackson. Whether or not the Florida peninsula is due to a buried ridge of ancient rocks, as is indicated by the results of at least one test well, a few moderate uplifts are found in Florida and southern Alabama that are certainly not salt domes. It would appear that Mississippi River constitutes approximately the easternmost limit of such structures.

Again, to the south-west, in Tamaulipas and Vera Cruz, the coastal plain is penetrated by large and small masses of basic igneous rock in the form of mountain masses, necks and dykes, faults and other structures. Still farther south (600 miles from the United

[12] F. H. Lahee, "Oil and Gas Fields of the Mexia and Tehuacana Fault Zones, Texas," Structure of Typical American Oil Fields, Amer. Assoc. Petr. Geol., 1929, vol. I., 304–88.

[13] H. E. Miner (p. 554), in "Goose Creek Oil Field, Harris County, Texas," Geology of Salt Dome Oil Fields, pp. 546–57.

States border) lies another great salt dome region, which is outside the province of the present paper, but is doubtless related genetically to the one in Texas and Louisiana.

Most important to the occurrence and distribution of Gulf Coast domes are the great fault systems of central Texas. These furnish some intimation of what may underlie the coastal plain and be responsible for salt dome alignments. Moreover, actual observed alignments lead to the hypothesis that salt domes may owe their positions to the intersection of sub-surface fault planes. There is no doubt that the "Five Islands" lie on a tectonic line,[14] and it is reasonable to suppose that Edgerly, Sulphur, Welsh, Evangeline and Anse la Butte do likewise.[15] Many such possibilities can be cited throughout the coastal plain of the two States.

As to detailed geological structure, every dome is a study by itself. No two are identical in contour or contiguous "sand" conditions. The salt in some of the domes lies practically on the earth's surface, but such is not true of those that are productive of oil in this petroliferous province. In other cases the salt masses may be buried at depths of a mile or two. The surface topography may be flat or it may be domed to over 100 ft. above the surrounding plain. In the majority of cases no surface doming exists, although the sub-surface structural relief may amount to 5,000 to 10,000 ft. In exceptional cases the position of the structure is evinced by a rim of low outcrop hills, in the centre of which lies a solution depression and sometimes a lake.

With the possible exception of the "Five Islands," the most satisfactory domes in either State in which to study the mechanics of the structures are some of the "interior" group. For this reason a tabulation, by Powers,[16] of a few of these domes, is quoted in full in Table III.

Production.

The production of petroleum from Gulf Coast salt domes in 1929 was 56,183,750 barrels, an increase from 45,950,247 barrels in 1928. The average daily production at the end of the year was 153,930 barrels. During the year there had been 1733 completions, of which 648 were failures, 64 were gas wells and the balance produced oil—a total initial daily production of about 600,000 barrels. In the same twelve months 30 new domes had been discovered, on which 14 new oilfields had been opened in previously unproductive areas. The

[14] A. F. Lucas, *Trans. Amer. Inst. Min. Engrs.*, 1899, **29**, Fig. 1; C. W. Hayes and William Kennedy, Bulletin 212, U.S. Geol. Survey, 1903, 144; G. D. Harris, Bulletin 429, U.S. Geol. Survey, 1910.

[15] F. G. Clapp (p. 582), in "Revision of the Structural Classification of Petroleum and Natural Gas Fields," *Bull. Geol. Soc. America*, 1917, **28**, 553–602.

[16] Sidney Powers, *op. cit.*, p. 222.

TABLE III

CHARACTERISTICS OF "INTERIOR" DOMES.

Name.	Salt core.	Cap-rock.		Saline, "licks," or lake.	Wells.		Geology.		Amount of Uplift in Strata.	Diameter of area Uplifted.
		Found.	Shallowest known depth (feet).	Top eroded.	Diameter (miles).	Mined during Civil War.	Found.	Depth (feet).	Central.	Circular around central hill.	Deepest on top of dome (feet).	Deepest on side of dome (feet).	Normal Surface Formation.	Oldest Formation Outcropping.	Feet.	Miles.
Texas:																
Grand Saline		×	225	Yes	1½	Yes	×	185	×		680	3,548	Wilcox	Wilcox	500	2½
Steen		×	320†	Yes	1	Yes	×	75	×		660†	2,630	Mt. Selman	Wilcox	500	3
Brooks		×	220	Yes	1½	No.	×	195	×		420	2,193	Mt. Selman	Austin	4,300	3½
Palestine		×	2,162	?	1	No.	No	—	×		3,170	3,046	Mt. Selman	Taylor	3,500	4½
Butler		×	312	?	1	No.	×	120†	×		700	1,200	Wilcox	Brda	5,500	3½
								—	×		1,200	1,200	Wilcox	Navarro	2,500	3½
Louisiana:																
Bistineau		×	1,662	Yes	1½	Yes	×	1,420	×		2,305	3,245	St. Maurice	Marlbrook	1,500	2½
Vacherie		×	777	No.	1×1½	No.	×	658	×		997	2,548	St. Maurice	Arkadelphia	1,500	4
Anacoco		×	1,400	No.	1½	No.	×	1,375	×		4,013	3,460	St. Maurice	Arkadelphia	2,350	3×4
Bayboun		×	1,115	No.	1½	Yes	×	At surf.	×		277	3,003	St. Maurice	Blossom	2,200†	4
Kisatchie		×	175	Yes	1	Yes	×	160	×		136	2,225	St. Maurice	Marlbrook	2,000	3
Price		×	1,300†	?	?	Yes	×	1,100†	×		None	?	St. Maurice	Wilcox	1,500	3
Prothro		×		?	1×1½	No.	×		×		None	None	St. Maurice	Blossom	3,000	2½
Drake		×	900	Yes	1½	No.	×	290	×		2,313	1,610	St. Maurice	Wilcox	1,500	2½
Winnfield		×	999	No.	1½	Yes	×	At surf.	×		1,110	4,021	Cockfield	Wilcox	2,000	3
Cedar Creek		×				No.	×	601	×		700	3,150	Cockfield	St. Maurice	1,500	3
Cocchie Brake		×	—	—	1	No.	×	—	×		None	3,100	Cockfield	St. Maurice	1,500	2½
Clear Lake		×	2347	?	1	No.	×	—	×		None	3,463	Cockfield	St. Maurice	1,500†	2½
Gibsland		×	1,238	?	—	No.	×	1,142	×		1,520	—	St. Maurice	—	1,000	2

total production of oil from salt domes in 1929 was, according to the *Oil and Gas Journal*[17] (revised to eliminate coastal fields other than salt domes), distributed as follows :—

TABLE IV.

Total Production in 1929.

Field.	Parish (in Louisiana) or County (in Texas).	State.	Production (barrels).
Allen	Brazoria	Texas	3,912
Barbers Hill	Chambers	"	4,523,350
Batson	Hardin	"	492,144
Big Creek	Fort Bend	"	1,452,522
Blue Ridge	" "	"	1,244,058
Brenham	Washington	"	81,761
Boling	Wharton	"	605,458
Clay Creek	Washington	"	796,434
Damon Mound	Brazoria	"	221,592
Fannett	Jefferson	"	324,901
Goose Creek*	Harris	"	2,172,128
High Island	Galveston	"	518,622
Hull	Liberty	"	3,488,869
Hankamer	"	"	25,527
Humble	Harris	"	2,996,409
Lost Lake	Chambers	"	98,377
Markham	Matagorda	"	162,318
Nash	Fort Bend	"	202,379
North Dayton	Liberty	"	219,435
Orange	Orange	"	1,066,726
Orchard	Fort Bend	"	44,187
Pierce Junction	Harris	"	5,193,061
Port Neches	Orange	"	241,815
Raccoon Bend	Austin	"	2,082,595
Saratoga	Hardin	"	347,686
Sour Lake	"	"	981,412
South Liberty (South Dayton)	Liberty	"	2,207,257
Spindletop	Jefferson	"	10,183,684
Sugarland (Dewalt)	Fort Bend	"	4,016,401
West Columbia	Brazoria	"	2,441,432
Anse la Butte	St. Martin	Louisiana	19,154
Bayou Bleu	Iberville	"	10,965
Bayou Bouillon	"	"	82,225
Black Bayou	Cameron	"	32,508
Dog Lake	Terrebonne	"	3,468
Edgerly	Calcasieu	"	281,498
Hackberry	Cameron	"	1,942,785
Jennings	Acadia	"	593,079
Lake Barre	Terrebonne	"	49,966
Lake Pelto	"	"	26,335
Lockport	Calcasieu	"	1,384,455
New Iberia	Iberia	"	2,090
Port Barre	St. Landry	"	44,558
Sorrento	Ascension	"	117,027
Starks	Calcasieu	"	174,758
Sulphur	"	"	1,357,911
Vinton	"	"	1,567,807
Welsh	Jefferson Davis	"	42,426
White Castle	Iberville	"	14,284
Total production of salt dome fields in 1929			56,183,750

* Not yet demonstrated to be a salt dome.

[17] Neil Williams, Jan. 30, 1930, p. 167.

On January 7, 1930, a new field was opened at Moss Bluff, in Liberty County, Texas.

A peculiarity of the salt domes in this geologic province is that the oil usually lies on the flanks, where held in "sands" that dip away into the surrounding basin, and thus the deposits are quaquaversal in their relationships. Although the production has not always been found to entirely surround a dome, it may occur all the way around, and in some of the domes it overlies the crest, either in the "cap-rock" or in gently-domed "sands." The oil ranges in gravity from 11° to 42° Beaumé (the higher figure being found at depths of over 5000 ft. below the surface of the Humble field); but the usual gravities are between 20° and 30° Beaumé. Individual wells have ranged from small producers up to as much as 84,000 barrels per day; and individual gas wells have been obtained with open flow capacities as high as 90,000,000 cu. ft., according to authentic reports.

Manner of Discovery.

In the early days of the oil business the attention of operators was called to certain areas of slight surface doming, to gas seepages, salt springs and "paraffin dirt." In recent years most of the discoveries of the Gulf Coast District have been made through the use of geophysical methods—torsion balance and seismograph—and the respective advocates of these two methods are still contending for leadership.

Out of 39 domes that are reported to have been discovered by geophysical methods in Louisiana, 13 are already productive of oil or gas, viz., Sorrento, Starks, Black Bayou, East Hackberry, Fausse Point (Loreauville), Vermilion Bay, Bayou Bleu, Bayou des Glaises, White Castle, Chacauhoula (Lutcher or Thibodaux), Dog Lake, Lake Pelto and Lake Barre. In addition, six productive domes were opened in 1929 in Texas on the basis of geophysics, viz., Esperson, Hankamer, Lost Lake, Moss Bluff†, Mykawa and Port Neches. Fields in the same State that had previously been discovered on the basis of geophysics are Allen, Fannett, Orchard and Sugarland (Dewalt). In some of the geophysically prospected fields that have not been proved productive of oil, the presence of salt is already proven. Table V. outlines, so far as practicable the results of drilling in the Gulf Coast District on the basis of geophysical "discoveries." The tabulation has been revised with the assistance of Dr. Donald C. Barton from the original lists by Jack Logan, published in *Oil Weekly*.

† Opened early in 1930.

TABLE V.

Geophysical "Discoveries" in the Gulf Coast District.

Texas.

Locality.	County.	Method.	Date.	Results.
San Felipe	Austin and Waller	Torsion and seismic.	1927	Sulphur water, cap rock.
Allen	Brazoria ..	Torsion	1925	Oil.
Clemens	,, ..	,,	1925	Dozen unsuccessful tests.
Sandy Point†	,, ..	Seismic	1929	Undrilled.
Devils Elbow† ..	,, ..	Seismic and torsion.	1928	,,
Fresno†	,, ..	Torsion	1930	Drilling.
Danbury	,, ..	Seismic	1929	Little oil.
Pledger†	,, ..	Torsion	1929	Undrilled.
Manvel	,, ..	,,	1929	Oil and gas showings.
Pala Blanca	Brooks	Seismic	1929	Gas with oil showings.
Lost Lake	Chambers ..	,,	1927	Oil.
Anahuac†	,, ..	,,	1928	One unsuccessful test.
Oyster Bayou* ..	,, ..	Torsion	1929	Drilling.
Cove	,, ..	Seismic	1929	Slight oil showings.
Altair*	Colorado ..	,,	1925	No deep tests.
Long Point	Fort Bend ..	Torsion	1924	Sulphur mining.
Orchard	,, ,, ..	Seismic	1924	Oil.
Sugarland (Dewalt) ..	,, ,, ..	Torsion	1927	,,
Needville	,, ,, ..	,,	1928	Two failures.
Smithers Lake† ..	,, ,, ..	,,	1928	Undrilled.
Clodine	,, ,, ..	,,	1929	Two failures.
Rosenberg	,, ,, ..	,,	1929	One failure.
Hitchcock†	Galveston ..	Seismic	1929	Undrilled.
San Leon†	,, ..	,,	1929	,,
Arriola	Hardin ..	,,	1928	,,
Grigsby†	,, ..	Torsion	1929	,,
Deer Park†	Harris	,,	1928	Showings reported; one test.
Genoa	,, ...	,,	1928	Gas.
Mykawa	,, ...	,,	1928	Gas and little oil
Satsuma†	,, ...	,,	1928	Undrilled.
Cedar Bayou† ..	,, ...	Seismic	1929	Showings in two tests.
Eureka†	,, ...	Torsion	1929	One test; failure.
Ogburn Survey† ..	,, ...	,,	1930	One test; oil showings.
Francitas†	Jackson ..	Seismic	1929	Undrilled.
Fannett	Jefferson ..	,,	1925	Oil.
Hamshire†	,, ..	,,	1928	Oil showing; one deep test.
McFadden Ranch ..	,, ..	,,	1928	Undrilled.

* Geophysical structural high; not supposed to be a salt dome.
† Geophysical anomaly; character of structure not clear.

TABLE V—*continued.*

Texas—continued.

Locality.	County.	Method.	Date.	Results.
Cheek†	Jefferson.	Torsion	1929	Undrilled.
Moss Bluff	Liberty	Seismic	1926	Oil.
Esperson	,,	Torsion	1928	,,
Hankamer	,,	Seismic	1928	,,
Heiskell	,,	,,	1930	Drilling.
Hawkinsville	Matagorda	,,	1925	Over 20 tests, known dome, but no oil.
Citrus Grove	,,	Torsion and seismic.	1930	One well drilling.
Shepherds Mott	,,	Torsion	1928	Two tests; showings.
Sargent	,,	Seismic	1929	Undrilled.
College Port†	,,	Torsion	1930	,,
Port Neches	Orange	Seismic	1928	Oil.
Vidor†	,,	Torsion	1929	Undrilled.
Texla†	,,	,,	1929	,,
Bloomington*	Victoria	,,	1929	Gas.
Beasley	Wharton	,,	1929	One failure.

Louisiana.

Locality.	County.	Method.	Date.	Results.
Egan	Acadia	Torsion	1927	Deep test; no showings.
Iota	,,	Torsion and seismic.	1929	Drilled to 6625 ft.
Darrow	Ascension	Seismic	1927	One deep test; no showings.
Sorrento	,,	,,	1926	Oil.
Napoleonville	Assumption	,,	1926	Known dome; no production.
Starks	Calcasieu	,,	1925	Oil; sulphur possibilities.
Iowa	Calcasieu-Jefferson Davis	,,	1929	Undrilled.
Hays City	Calcasieu-Jefferson Davis	,,	1929	,,
Black Bayou	Cameron	,,	1927	Oil.
East Hackberry	,,	,,	1927	,,
Lake Misere†	,,	,,	1927	Undrilled.
Calcasieu Lake	,,	,,	1927	Salt; 6 tests; no oil.
Mallard Bay†	,,	,,	1928	7200 ft. test; failure.
Cameron Meadows	,,	,,	1928	Frist test drilling; good showings.
Fausse Point (Loreauville)	Iberia	,,	1926	Oil.

* Geophysical structural high; not supposed to be a salt dome.
† Geophysical anomaly; character of structure not clear.

TABLE V—*continued.*

Louisiana—continued.

Locality.	County.	Method.	Date.	Results.
Vermilion Bay ..	Iberia	Seismic	1927	Salt; 5 tests no oil.
Bayou Bleu	Iberville ..	„	1926	Oil.
Bayou des Glaises ..	„	„	1927	Salt but no oil.
Grosse Tete (Bayou Choctaw)	„	„	1927	Salt.
White Castle	„	„	1927	Oil.
Roanoke	Jefferson Davis	Torsion	1928	Fair showings.
Barataria (Lafitte) ..	Jefferson ..	Seismic	1929	Frist test drilling.
Chacahoula (Lutcher or Thibodaux).	La Fourche ..	„	1927	Score of tests; salt; no oil.
Leesville	„ ..	„	1928	First test drilling; oil showing at 5300 ft.
Wisner (Marchand) ..	„ ..	„	1928	No showings in 6400 ft. well.
Carenco	Lafayette ..	„	1928	Deep failure.
Potash	Plaquemines ..	„	1928	Undrilled.
Lake Grande Ecaille..	„ ..	„	1928	Fair oil, showing; salt found.
Lake Hermitage ..	„ ..	„	1928	Undrilled.
Spanish Pass	„ ..	„	1928	„
Garden Island Bay ..	„ ..	„	1928	Salt; oil showings.
Lake Lery (Olivier)† .	St. Bernard ..	„	1928	Undrilled.
Lake Netherland ..	St. Charles ..	„	1928	„
Port Barre	St. Landry ..	„	1926	Oil.
Garland†	„ ..	„	1929	Undrilled.
Bayou Chene† ..	St. Martin ..	„	1929	„
East Bay Junop ..	Terrebonne ..	„	1927	Two tests; cap rock; no oil.
Dog Lake	„ ..	„	1928	Oil.
Four Isle	„ ..	„	1928	Three tests; salt; no oil.
Bay St. Elaine ..	„ ..	„	1928	Gas production.
Lake Pelto	„ ..	„	1928	Oil.
Lake Barre	„ ..	„	1928	„
Caillou Island ..	„ ..	„	1928	„
White Lake†	Vermilion ..	„	1929	Undrilled.
Gueydan	„ ..	„	1929	„
Abbeville†	„ ..	„	1929	No shows in 5000ft. test well.

ORIGIN.

In touching on the question of origin of the salt domes, the writer enters a controversy that has raged among geologists for the past 70 years. Many theories have been advanced,[18] and not until

† Geophysical anomaly; character of structure not clear.

[18] Summarized and correlated, with complete references, by E. De Golyer, "Origin of North American Salt Domes," Geology of Salt Dome Oil Fields, 1926, pp. 1–42; and A. G. Wolf, "The Origin of Salt Domes, a Chronological Tabulation of Theories Thus Far Advanced," *Eng. and Min. Journ.*, 1923, **115**, p. 412.

the past ten years have European views of the intrusion of an older salt mass through flowage seemed to be generally accepted. The sedimentary nature of the original salt mass is now practically proven by the discovery of salt-containing fossil algæ and potash compounds in the cores of one or more salt domes.

Many reasons exist for the inference that the salt masses are intruded from a pre-existing sedimentary deposit. De Golyer[19] quotes E. T. Dumble and Charles Schuchert as advocating the Lower Cretaceous strata as the probable source of the salt, and Schuchert himself confirms this view.[20] Nevertheless, the concensus of opinion seems to be that the salt is either of Permian or of Triassic age.

As evidence of the generally prevalent opinions, Avery Island may be cited. In sinking a mine shaft the salt was found to enclose an irregular mass of tough red sandstone about 75 ft. long,[21] strongly suggesting a derivation from[22] "certain Permian rocks of the Texas Panhandle, even in such details as fineness of grain, secondary growth around the quartz grains, and colouring matter. Furthermore, surface rock in the Texas Panhandle is often associated with great beds of salt."

But similar rocks exist elsewhere, and one included mass constitutes no proof of the age of the salt. Whether it be Mesozoic or Paleozoic, its intrusion into the Cretaceous, Tertiary and Quaternary sediments appears to have been comparatively recent. A large part of the movement may have taken place between Wilcox and Claiborne time in the early Tertiary period. The existence of some topographic elevations overlying salt domes in the otherwise flat coastal plain appears to constitute an evidence of late movement, for[23] "In one case . . . the dome was still rising in 1925 and 1926 at a rate of about six inches a year, as shown by spirit levelling on to bench marks at a distance from the dome: That is, the ground surface was rising." That writer goes on to show that this fact does not constitute absolute evidence of the present rising of the salt, for the surface rising may have been caused by expansion in volume of anhydrite during its recrystallization into gypsum.

Evidence of recent uplift is also found in the "Five Islands."[24] For instance, on Jefferson Island the elevated position of fossils

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[19] *Loc. cit.*

[20] Charles Schuchert, Discussion of Paper by De Golyer, *op. cit.*, pp. 42–3.

[21] G. S. Rogers, "Intrusive Origin of the Gulf Coast Salt Domes," *Econ. Geol.*, 1918, 13, pp. 447–85.

[22] Vaughan, *op. cit.*, p. 393.

[23] Harry Pennington, *Oil Weekly*, Jan. 1, 1929.

[24] Vaughan, *loc. cit.*

indicates that the island "was probably uplifted in very late Pleistocene or post-Pleistocene time. At Belle Isle a recent uplift is evinced by beds containing recent fossils, dipping at an angle of 25°."

The linear distribution of some groups of salt domes suggests that they may be situated at the intersection of Paleozoic fault planes or other points of Paleozoic weakness, which have caused movements favourable to upward migration of salt in its plastic condition. A downward pressure of the sedimentary basin, settling under the influence of gravitation and of isostatic conditions may have permitted the actual upward movement of the salt.

The "Cap-Rock."

A much discussed concomitant of Gulf Coast salt domes is their calcite ("limestone" in the parlance of the well drillers) or anhydrite (widely altered to gypsum) "cap rocks." These substances, generally but not always present in the domes of this petroliferous province, are, according to some opinions, sedimentary in origin, like the salt itself, whereas other geologists consider them alteration products. In some of the domes the "cap rock" flanks the salt masses as well as crosses their tops.

"Cap rock" has been discussed in detail by De Golyer[25] and Rogers[26] and more recently by Goldman.[27] The last-named writer, who differs from any geologists, considers the anhydrite caps to be "part of an original bed of anhydrite which overlies a bed of sedimentary salt at depth." The usual flat upper surface of the salt mass is believed by him to owe its existence to the protection furnished by the overlying anhydrite bed. Calcite "cap rocks" however, he believes to be replacement deposits.

The occurrence of sulphur in some salt domes is important economically and scientifically. At Sulphur, Louisiana, for instance, an anhydrite "cap rock" 1100 ft. thick is overlain by a sulphur bed that sometimes fills irregularities in the anhydrite surface and is overlain in turn by "limestone" (called "cap rock" by the sulphur operators, in contradistinction to the same term when used by the oil operators for the aggregate of "limestone" or calcite, sulphur and anhydrite or gypsum, or any combination of them).

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[25] E. De Golyer, "Origin of the Cap Rock of the Gulf Coast Fields," *Econ. Geol.*, 1918, **13**, 616–20.

[26] G. Sherburne Rogers, Discussion of De Golyer's Paper, *Econ. Geol.*, 1919, **14**, 178–80.

[27] M. I. Goldman, "Petrography of Salt Dome Cap Rock," Geology of Salt Dome Oil Fields, 50-86.

Conclusion.

In the present paper the details of stratigraphy, structure, economic criteria, theories of origin, etc., have been intentionally omitted, since they can be found in many papers previously published. The aim of the present writer is to condense in one place the outstanding features regarding the Gulf Coast salt domes, so that interested persons outside the United States who may desire to learn the essentials of this district or to compare these domes with those of other salt dome districts, may not be obliged to search through a great mass of literature to gain the principal facts. In any more extended consideration of the domes the extensive literature concerning the details may be consulted. A complete bibliography of the subject would prove rather voluminous: but the more important papers may be found by referring to bibliographies and footnotes given in the works mentioned in this paper.

Salt Domes in Persia.*

By J. V. Harrison, B.Sc., F.G.S.

1.—Introduction.

One hundred and thirteen salt plugs are now known in the region adjoining the Persian Gulf and others await discovery. Literature dating from 1872[1] deals specifically and generally with some of these occurrences, and within the last four years G. M. Lees,[2] R. K. Richardson,[3] H. de Böckh,[4] F. D. S. Richardson[4] and the writer have described some of the phenomena in greater or lesser detail.

The present paper is an attempt to summarise knowledge of the Persian salt domes in the light of the most recent observations, and to offer certain speculations regarding their distribution and causes.

(11). Geographical Distribution.—The salt plugs of Persia are found in two provinces: the majority burst through the folded sediments bordering or covered by the Persian Gulf, while some occur on the north-eastern edge of this folded zone, where faults are abundant. The others pierce the Mio-Pliocene deposits of the Median Mass,[4] which builds much of the high plateau of Central Persia.

From the point of view of origin, two types of salt plug can be distinguished, those which have come from shallow depth, and those which have come from great depth. The latter include much the larger number of the occurrences in the Persian Gulf Province, and are those which on account of their size and colouring have attracted most attention; but the former also deserve consideration.

(111). *The Persian Gulf Salt-plug Province* is sharply defined on the north-east by the front of the nappes,[4] which runs from near Gukan, and beyond, in the north-west, to Pur in the south-east; on the east by the nappes which form the Zindon Range; and on the south-east by a line running from near Shamil south-westwards approximately parallel to part of the Trucial Coast of Arabia. How far the outbursts of salt belonging to this province extend into Arabia is not known. Although much country is till unexplored towards the north-west, a line running from Jebel Sinam in Iraq to Baznui in Persia lies beyond all the salt plugs known near the

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Persian Gulf. In the south-east part of the province so defined they are very abundant, but towards the north-west there is a falling off in density of distribution, and a tendency to occur only in the thrust-faulted belt which lies just in front of the nappes. While Darreh Ti is at present the ultimate example known in the north, possibly there are others to be found still farther north-west; and to the south-east there are parts of the country not yet seen by geologists in which salt plugs are to be expected.

Salt plugs originating at shallow depth are also known in this province. One has broken through to the surface at Ambal, and somewhat analogous structures are known from drilling; but most of them are inferred from gypsum "bulges" and brine springs.

(112). *The Salt-plug Province in Central Persia* is a much smaller one, embracing country around Qum and Kuh-i-Gogird, about fifty miles south of Tehran. Little opportunity has occurred for these salt plugs to be studied, but short descriptions of them have recently appeared.[4] They are all believed to be of shallow origin.

(12). MORPHOLOGY.—From the shores of the Persian Gulf and from the banks of the River Tigris a strip of silt-covered flat country extends to near the base of an array of whale-back mountains of brown- or grey-coloured naked rock in part of the province, but in the northern part a strip of low red-and-white coloured hills formed of red shale and gypsum intervenes. In general, nearer the coast or plain, the dissection of these mountains has not gone far, so that the original dome-shaped forms, resulting from the geological structure, have not been destroyed, although their sides may be deeply gashed by narrow steep-sided valleys, or "tangs." Farther from the coast, and also exceptionally near it, many of these domes have been broken by thrust and normal faults. Erosion has cut deeply, so that secondary land-forms appear, such as mountains sculptured out of synclines, or serrated crags of "dip and scarp" type.

Almost everywhere exposures are good because vegetation is sparse. Rainfall varies considerably from year to year and from coast to mountains. It lies between 2 in. and 30 in. per annum approximately, according to the proximity of the high ranges. It increases from the south-east towards the north-west.

(121). *Salt-Hills.*—In such bare, juvenile landscape, the appearance of salt-plugs introduces sharp discordances of morphology and colour. The even curves of a dome are abruptly broken and the beds upturned where a salt-plug has broken through in more recent times; or the smooth contours end, and an oval pit marks the site of an older salt-stock which has been washed out; or a fantastically-pinnacled rudely-shaped salt-hill projects above the

Fig. 1. SKETCH MAP SHOWING THE TWO PROVINCES IN WHICH SALT-PLUGS OCCUR IN PERSIA.

regular slopes. The unobtrusive khaki and dull-grey of the region is broken by a patch of variegated colours. A pink or terra-cotta tint dominates most of the salt-hills. In sharp contrast with this stand out the white and grey bands of the rock-salt, occasionally streaked with gleaming white by recrystallisation; and the dull-white gypsum, dark-green dolerites, and black fœtid dolomites which invariably accompany it. There are besides rarer patches of yellow shale and purple sandstone, the latter sometimes interbedded with pale-green silt. The medley of colours within the limits of a salt-plug is entirely devoid of symmetry or regularity of any kind; it resembles no other natural grouping of colours and must be seen to be appreciated.

Where a salt-plug has broken through in recent times and its girdle of sediments is still complete, the salt at first builds a mountain which looks like the mould of an inverted coffee-cup (Fig. 2). As the girdle of sediments breaks down and peripheral drainage finds an outlet, this mould-shape deteriorates through erosion to form a comparatively gentle domal hill lying within a rampart of sediments (Fig. 3). The zone of sediments nearest to the salt has invariably been shattered by the intrusion and is therefore liable to very rapid erosion. Consequently, the dome-shaped salt-hills tend quickly to surround themselves with a ring of alluvium which separates the salt from the less disturbed part of the sediment-sheath. The dome-shape of the salt-hills at this stage in their decay is far from perfect, since the salt is mingled with materials unequally resistant to weathering; blocks of dolomite or dolerite resting on the salt form pinnacles, just as rock-slabs do on a glacier.

Where erosion of the sheath has gone further a relatively flat-topped hill of salt may remain. The sides of such a salt-hill rise steeply from the alluvium lying between the salt and the weathered-back rim of sediment (Fig. 4).

The final form produced by the complete weathering down of the rim is a circular steep-sided, flat-topped hill of salt, rising from an alluvial plain (Fig. 5). In the flat-topped form of salt-hill projecting pinnacles and ridges are very subsidiary, though locally conspicuous features.

(122). *Salt Glaciers.*—In the forms just described the salt has behaved like an ordinary rock when once the injection has been effected, and has been passive under the action of the weather. Other striking forms occur, however, in which the salt, gypsum, and red shale, which together make up the bulk of the injected material in an average salt-plug, are not passive after injection, but exhibit mass-movements which can be compared with the flow of glaciers and give rise to distinctive land-forms.

Fig II.

Fig III.

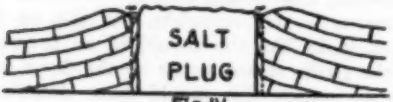

Fig IV.

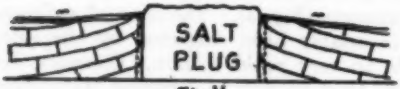

Fig V.

Fig VI.

Fig VII.

Fig VIII.

In the first case, the sedimentary girdle is lowered by erosion on one side and the salty materials overflow it, assuming a cascade-like form with a steep gradient. This phenomenon was first described and sketched from the Anguru salt-plug by G. M. Lees,[2] who called the occurrence a "salt-glacier." Through the sheet of outpoured saline matter peaks of the underlying sheath of the salt-plug may project as depicted by Lees. Some of the features are perhaps more of the nature of landslips and rock-falls; but the salt appears to be able in some way to reunite into a coherent mass—though the mechanism of the process may be different from the regelation of glacier-blocks below an icefall.

In the second case, when erosion has produced a low breach in the rim of sediments, the salt sometimes issues as a gently inclined tongue from the side of the salt-dome (Fig. 6). In two instances such a tongue reaches a distance of three miles from the margin of the salt-dome, and has a width of fully a mile and a-half. The thickness of the protruding sheet is about 200 feet and has a general tilt outwards from the salt dome of about 5°. The surface of the sheet is not smooth, but is crevassed and weathered with the production of sinkholes.

A variety of the second type is found where all the sheath of sedimentary rock has been eroded down to or below the present plain-level, and the salty material has flowed away from the central boss in all directions. This surrounding apron-like sheet has the same gentle inclination from the centre to near its edge; but this edge is steep and rises in a cliff from the alluvium (Fig. 7).

(123). *Solution Cauldrons.*—In addition to the more usual positive landforms, salt intrusions give rise also to some negative features. Instances have been observed in which removal of the soluble parts of the dome-material has far outstripped the weathering down of the ensheathing sedimentary rocks and has led to the formation of a cauldron, floored with the clays and other insoluble constituents of the salt complex, forming sometimes hills of considerable size (Fig. 8). The height to which the cauldron was originally filled by the intrusion is sometimes registered by red staining on the enclosing walls.

(124). *Solution Valleys.*—Along the north-eastern margin of the Zone of Folding, where there has been considerable thrust-faulting, the weathering out of the saline material which is sometimes found in squeezed masses along thrust-lines, produces deep attenuated valleys following approximately the course of the fault-zone. A salt-body occurring near a thrust-fault, especially if the fault has determined one side of it, has generally weathered away more quickly than the rocks in contact with it, and a negative feature is formed.

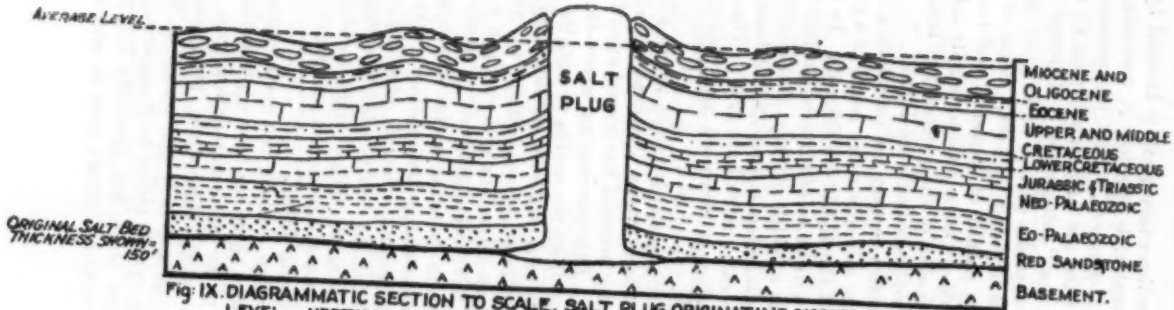

Fig: IX. DIAGRAMMATIC SECTION TO SCALE. SALT PLUG ORIGINATING 21000FT BELOW AVERAGE LEVEL. VERTICAL AND HORIZONTAL SCALE 1 INCH = 17000 FEET. ORIGINAL SALT BED 150' THICK OVER A SQUARE WITH 16 MILE SIDE (LENGTH OF SECTION) SUFFICIENT TO PRODUCE A CYLINDRICAL PLUG 1½ MLS. DIAMETER

Mesozoic

Kainozoic

(125). *General Features.*—All these landforms are associated with salt-plugs that have risen from great depth, and—except where disturbed or deflected by thrust faults—have reached the surface through vents that are roughly circular or oval, though the shape may be obscured by irregular marginal outflow.

2.—Stratigraphy.

A comparatively complete sequence of strata has been established in the Persian Gulf province from Lower Cambrian to Pleistocene and Recent. The gaps that remain are perhaps more apparent than real, since considerable thickness of beds have so far yielded no fossils, and further research may hope to produce much additional detail-knowledge. All the rocks have been laid down in a basin of sedimentation apparently undisturbed by igneous activity since Cambrian times.

The generalised, approximate sections set forth below, one for Laristan and one for Bakhtiari-land, are designed to give some idea of the beds through which the salt has had to force its way.

	Laristan.		Bakhtiari-land.
Kainozoic	Up to 2000 ft. Coarse limestone conglomerate.	Up to 6000 ft.	Coarse limestone conglomerate.
	Up to 10,000 ft. Greenish silt and sandstone.	Up to 5000 ft.	Red sandstone and shale.
	Up to 3800 ft. Muddy reef-limestone and grey shale; Vindobonian fauna.	Up to 2000 ft.	Greenish muddy limestones and shales.
	Up to 1300 ft. Bedded gypsum with red marls, sandstone and conglomerate. Lower Miocene.	Up to 3000 ft.	Bedded gypsum and salt with red and grey marls. Lower Miocene.
	Circa 500 ft. . Variable from muddy limestone to thin red sandstone, *Nummulites intermedius* common. Oligocene.	Circa 1000 ft.	Massive limestone (Asmari).
		500 ft. . .	Shaley limestones with *Nummulites intermedius*. Oligocene.
	Circa 2000 ft. Massive and well-bedded nummulitic limestone with dolomites. Eocene.	Circa 1500 ft.	Nummulitic limestone, muddy limestone, red conglomerates and sandstones. Eocene.
Mesozoic	Up to 900 ft. Bedded gypsum.	1500–3000 ft.	Soft marls, flysch-sandstone reef-limestones and dark shale. Upper Cretaceous.
	Circa 3000 ft. Massive limestones, rubbly limestone, marls and shales with rudists, etc. Cretaceous.	Up to 5000 ft.	Massive rudist-limestones with chert at base. Middle Cretaceous.

	Laristan.		Bakhtiari-land.
Mesozoic	Circa 1500 ft. Dark dolomite, white and grey limestone with *Belemnites*, *Rhynchonella*, *etc.* Jurassic.	Circa 1500 ft.	Ammonite-shales and thin limestones. Lower Cretaceous.
		Circa 1000 ft.	Dark dolomitic limestones with algæ *Rhychonella* and ammonites. Jurassic.
	Circa 2000 ft. Multiple-bedded brown-weathering limestones. Triassic ?	Circa 1600 ft.	White siliceous limestones and brown sandy limestone. Triassic ?
Neo-Palæozoic (?)	Circa 3000 ft. Dark massive and and multiple-bedded fossiliferous limestone. *Fenestella*, *Lonsdalia*, etc. Carboniferous.	Circa 1400 ft.	Light-grey dolomite, oolite, and sandy limestone, rare *Productus*. Permo-Carboniferous.
		Circa 1400 ft.	Dark massive and multiple-bedded fossiliferous limestone *Fenestella*, *Fusulina*. Carboniferous.
	Circa 400 ft. . White quartzitic sandstone and dark grey shale. Devonian ?	Circa 100 ft. .	White quartzitic sandstone with worm-tubes. Devonian ?
Eo-Palæozoic (?)	Circa 200 ft. . Dark shales with *Monograptus*, *Diplograptus*, etc. Lower Silurian ?	Circa 1700 ft.	Soft brown shale with a little sandstone. Silurian ?
		Circa 200 ft. .	Quartzitic sandstone and shale. Ordovician ?
	Circa 50 ft. . . Saccharoidal white quartzite. Ordovician ?	1300 ft. ..	Green micaceous shale with fucoid-marks and dark fossiliferous limestone, *Billingsella*(?) etc., Upper Cambrian.
	500 ft. .. Green shales, micaceous and fucoid-marked. Thin quartzite-ribs. Cambrian.	Circa 1400 ft.	Striped purple, green and yellow shales and marls. rare trilobites, Middle Cambrian.
		Circa 1900 ft.	False-bedded red sandstone. Lower Cambrian.

21. Eo-Palæozoic.—From these columns it is clear that up to the base of the Neo-Palæozoic quartz-sandstones and micaceous shales are dominant, though limestones are not unimportant. The Eo-Palæozoic beds have yielded a fairly varied fauna which, although it is not usually abundant, has allowed determinations of Middle Cambrian, Upper Cambrian, and Lower Silurian horizons. Other ages are tentative.

22. Neo-Palæozoic and Mesozoic.—After the first few hundred feet of strata, limestones predominated through the Neo-Palæozoic and Mesozoic, and in the south continued to do so until Miocene times. No major break is recognisable during this long interval. Fossils have been found assignable to Carboniferous, Permo-Carboniferous, Jurassic, Cretaceous and Kainozoic. Only in the beds relegated on account of their position to the Triassic have no identifiable fossils been collected.

23. Kainozoic.—With the beginning of the Kainozoic the wide-spread even conditions of sedimentation ended. Coarse sandstones and conglomerates were formed in the Eocene, Lower Miocene, Mio-pliocene and Pliocene; but up to Lower Miocene times there were occasional periods of quiet sedimentation which permitted local accumulation of thick limestone-beds. Since Middle Miocene times, however, abundant coarse detritus has been undergoing transportation, so that imposing conglomerates and thick sandstones are the outstanding deposits.

24. "Hormuz Series."—The salt and gypsum masses of the salt-plugs, with the associated red-beds, probably belong to early Cambrian and indicate that a period of aridity and tectonic quiet followed the close of Pre-Cambrian time. Earlier work in the Persian Gulf (Blandford, 1871; Pilgrim, 1907) did not appreciate the heterogeneous character of the other rocks that are associated with the salt, but designated all together as "Hormuz Series." The first adequate explanation of this "series" was published by de Böckh, Lees and Richardson,[4] who showed that it is no true stratigraphic unit, but a haphazard aggregation of fragments of other formations carried upwards and brought together by eruptive movement of salt.

(241). *Cambrian and Younger Sedimentary Rocks.*—The finding of trilobites by G. M. Lees in this assemblage of rocks was the first indication that Cambrian strata were present. More is now known about the stratigraphy of the province and it is comparatively easy to recognise, in the rock-fragments of the "Hormuz Series," pieces torn from the Lower Cambrian red sandstones, the Middle and Upper Cambrian limestones and shales, the grey dolomites of the Permo-Carboniferous, the yellow-brown calcareous sandstones of the Trias, and occasionally typical algal limestone from the Jurassic.

The "Hormuz Series" as seen in the salt-plugs is made up of rock-salt, gypsum, and abundant red and terra-cotta-coloured clay, together with masses (which may be whole hills or only small boulders) of igneous rocks, dark limestones and dolomites, red and grey sandstones and variegated shales. All the limestones and dolomites have undergone some slight chemical alteration chiefly through the agency of water, carbon dioxide, sulphuretted hydrogen and strong salt-solutions.

The rocks included in the Hormuz formation seem therefore to include blocks carried up by the salt from formations of Cambrian age and upwards. In addition there are components which have not yet been found in situ in the sediments of the Zone of Autochthonous Folding. These include the salt, gypsum, and red shale, which probably underlie the Lower Cambrian red sandstone* the base of which is not exposed; and the igneous rocks and various minerals.

(242). *Igneous Rocks, Metamorphic Rocks and Characteristic Minerals.*—The igneous rocks are mainly altered dolerites and basalts ("diabases") in which albitization and epidotization are characteristic features. Granite-porphyry, quartz-porphyry, kerotophyre, and felsite have also been found, though less abundantly, and also show some development of epidote. The collection included also a single pebble of mylonite with hornblende porphyroblasts, and one specimen of metamorphic limestone with grossular garnet.

The minerals collected from the "Hormuz Series" include quartz, in part as acicular bipyramidal crystals in limestone; dolomite; calcite; anhydrite; iron-oxides in the form of red earthy hæmatite, dull iron-grey hæmatite-concretions, and lustrous specular iron-ore in flakes and well-formed crystals; ilmenite; iron pyrites as perfect, interpenetrating-twinned, pentagonal dodecahedra, and as cubes; chalcopyrite; fibrus green gedrite; pale-blue fibrous hydrous magnesium silicate; bright-green prisms of epidote; and yellow nontronite.

The character of the igneous rocks makes it probable that they are not younger than Eo-Palæozoic, and the source of at least some of the minerals is likely to be the pre-Cambrian basement below the salt-deposits.

3.—Tectonics.

31. Folding.—The north-eastern borderland of the Persian Gulf is characterized by great elongated simple folds, which in the east trend E.N.E.–W.S.W., in the region of Lingeh approximately E.W. and in the rest of the area approximately N.W.–S.E. There is a general tendency for the northern limb of each anticline to be the

* There is a possibility that the red sandstone and the red saliferous rocks are lateral variants of the same age.

gentler one, and for the southern limb to be steep and not infrequently broken. The proportion of broken folds is greater along the north-eastern margin of the province and greatest of all towards the northern corner. Some of the anticlines have an elongation of as much as 120 miles, a width from syncline to syncline of 15 miles, and an amplitude of 15,000 ft. Individual folds are clear and distinct, even when they have suffered some thrust-faulting on their southern side, as far as the range of more rugged hills which forms the front of the nappes. There a totally different structure-pattern begins and north-eastwards for some miles folds cannot be distinguished.

The structures of the Median Mass—in which is found the second salt-plug-province—are shorter and narrower, and exhibit no general consistency of trend.[4]

(32). Faulting.—The faulting which disturbs this region of Persia is chiefly thrusting. No thrust-fault is known with a throw of more than 20,000 ft. at maximum; in most it is considerably less. The hade of these faults varies considerably: at out-crop the planes are usually steep; under-ground they curve and become gently inclined. With the maximum development of the faults it is common to find a zone of a crush-breccia, sometimes more than 100 ft. thick. Lenses of red shale, with rarely a few boulders of igneous rock, are also found near some of the fault-traces, and have been called "Hormuz-smears."

Tear-faulting is common, but the throw of such faults is small. They are normally found in the north-eastern limbs of the broken folds, disturbing the lower limestone-formations and tending to die out in shale-beds.

(33). Salt-Intrusion.—The salt-domes are found in general cutting through unfaulted anticlines, sometimes at a crest maximum, sometimes at the plunging end, and sometimes on one or other flank quite indifferently. One or two seem to be located in the trough of a syncline.

Near the north-eastern margin of the province some salt plugs appear to have followed fault-lines, and some of the plug-material may have been dragged along by a moving thrust-mass; but the majority of the salt plugs that are in contact at the surface with Cretaceous or Kainozoic rocks have not followed fault-lines, at least near the surface, but have broken through in circular vents. Some of them may, perhaps, have been subsequently covered by overthrust-masses.

4.—Some Typical Persian Salt Plugs.

The following salt plugs are described as examples of the different types now known in Persia.

(41). KUH-I-SHUR salt plug is a cylindrical body of salt and gypsum with a little red shale which has burst through the crest of a structural dome. It has cut through and tilted Eocene and Cretaceous limestones, which now form a ring of upturned beds around the intrusion. The salt mass forms a nearly flat-topped hill rising 6,000 ft. above sea-level and 4,000 ft. above the neighbouring plain. It rises about 500 ft. above the highest point on the rim of sedimentary rocks. On the western side a stream has cut back to the salt, but has formed only a very narrow gorge through the limestone-sheath and is now rapidly cutting back along the zone of shattering which surrounds the salt, separating it from the undisturbed limestones. The age of this intrusion is certainly post-Eocene, as it has clearly disturbed the Eocene limestone. In view of its shape and the absence of any conglomerates in the Miocene it is thought to be post-Miocene and probably very recent.

This salt-plug of Kuh-i-Shur is the nearest approach seen to a simple cylinder of salt. The brown limestone of the original dome is pierced by a pink-coloured column of salt, and the form is not modified by advanced erosion or by outflow. The hill of salt carries very few blocks of extraneous material.

(42). KUH-I-KURDEH is a roughly dome-shaped hill of salt, with a ring of alluvium separating it from the limestones through which it was intruded. All signs of disturbance caused by intrusion have been removed from the surface by erosion. Cretaceous and Eocene strata adjoin the western half of the alluvial girdle. No important outflow has taken place. The salt rises at least 1000 ft. above the plain. The age of this intrusion is not post-Eocene but pre-Miocene, as the Miocene for a few miles around contains a thick bed of conglomerate, evidently derived from a hill pushed up by the salt.

The red-veneered dome of salt is strewn with abundant boulders and blocks of dark dolomite and limestone, red shale and sandstone, and dolerite, capping sometimes the familiar salt pinnacles. A notable block of Eocene limestone lies on its southern side.

(43). KUH-I-SIAH TAQ-I-GIRASHI is a well-shaped dome of salt, with a covering of red shale, situated in a great precipitous-walled pit on the northern side of the Kuh-i-Burkh anticline. Between the margin of the salt and the undisturbed limestone cliffs lies a flat-bottomed valley, about 200 or 300 yards wide, covered by alluvial gravel. The intrusion is a mile and a-half in diameter and rises over 1000 ft. above the Girashi plain. The limestone wall is breached on the northern side, and from the breach a tongue-like sheet of salty gypsum projects for about three miles over the alluvial plain beyond. The dome-shaped, red-coloured salt mass slopes steeply on all sides, whether to the girdle of alluvium or to the tongue of saline material which issues from its northern

foot. There is a sharp discordance in slope, therefore, between the surface of the dome and that of the projecting tongue. In colour the two differ also: the dome is pink, while the "glacier" issuing from it is white. The outward inclination of the "glacier" is less than 5°, and its margin rises steeply from the alluvium to a height of more than 50 ft. It carries on its surface blocks of dolerite and dolomite as well as shale, and these have protected pillars of the salty gypsum from erosion just as happens on the dome itself. Seen from a distance, this "glacier-sheet" appears to have a nearly flat surface, but closer inspection shows that it is gashed by small valleys, crevassed, and weathered into potholes.

The age of this salt-plug is certainly post-Cretaceous. Its form and state of preservation suggest that it is young.

(44). KUH-I-NAMAK-I-SHAH GHAIB is a salt-hill shaped rather like a steel helmet. In the centre a dome-like boss rises from a wide brim which slopes gently outwards in every direction. The "crown" of the helmet is made up of dull-grey and pink-stained salt and gypsum, embellished on the southern side with one large patch of khaki-coloured sandy limestone and a few green patches of igneous rock, while the "brim" is formed by a wide expanse of white and red-stained gypsum and salt, broken by many crevasses, and terminating abruptly against alluvium, or, on the western margin, against solid rocks.

The plug is certainly post-Miocene, the nearest solid outcrops show Miocene beds which dip towards it and must therefore have been pierced by it. The abrupt form of the "crown" must imply that an uprise of the salt has taken place very recently, since such material could not for long maintain itself against erosion.

(45). KUH-I-PALANGU presents a nearly flat-topped saline hill, with a steep margin, completely surrounded by alluvium. The marginal slopes are tolerably smooth, except for minor protuberances due to the protecting influence of extraneous rock-masses. No outflow seems to have taken place, since the shape of the hill is approximately oval; at any rate, none is now apparent. A low hill of dark dolomitic limestone is conspicuous on the north-western edge of the salt; other extraneous materials are the common types of sandstone, shale and limestone, with an exceptional abundance of keratophyre.

A post-Miocene age is perhaps to be deduced from the fact that Miocene limestones outcrop some two miles away and dip towards the salt mass.

(46). KUH-I-IRCHEH.—In the domal part of Kuh-i-Ircheh, a whale-back hill of Miocene limestone, some twelve miles long and five miles across, there is a remarkable cauldron-shaped hollow some two miles in diameter, with its walls pink stained to a con-

siderable height, and on its floor an abundant assemblage of blocks of red shales and sandstones, dark dolomites and limestones, as well as dolerite masses and mixed gravels—all materials typical of the "Hormuz Series." This cauldron is evidently the product of a salt-intrusion which began to break through in Lower Miocene times, as there are patches of conglomerate interbedded with the Lower Miocene, but did not cease moving until Upper Miocene, or later, as it has broken through the Vindobonian limestone which forms the skin of the whale-back hill. All the salt has been removed by solution down to water-level and is now covered by a mantle of gravel and clay, which seems to be impervious as fresh water is at present collected from the run-off. Egress for drainage is through a breach in the southern wall.

(47). Pir Alan Sabz.—Along the axis of Kuh-i-Pur there is a deep elongated valley called Pir Alan Sabz which coincides with a strip of "Hormuz Series." Banded dark-grey rock-salt and gypsum occur at the western end, and along most of the valley there are irregular patches of red shale and corroded dark limestones. The intrusion is post-Vindobonian in age and has followed the line of a small thrust-fault. No staining is visible on the walls of the valley, which rise high above the level of the salt- and shale-outcrops. Keratophyre is common in the debris here.

5.—Discussion of Special Problems.

(51). Age of the Salt-Plugs.—More or less detailed descriptions of seventy or eighty Persian salt-plugs have now appeared, and from these the age of the salt-intrusions is fairly well known. The majority of them have broken through in Pliocene or post-Pliocene time, as they have tilted up the green shales, silts and sandstones of Mio-Pliocene age which are themselves partly Vindobonian and partly post-Vindobonian. Some salt-plugs which appear in contact with upturned beds of much older date show by their youthful topography that they too are probably post-Pliocene. Others give clear proof of having been formed in pre-Pliocene times, for in their neighbourhood there are conglomerates in the Vindobonian, showing that uplift had already caused local emergence at the time when the Vindobonian beds were being deposited. Such conglomerates have been encountered at Kuh-i-Kurdeh, Kuh-i-Ircheh and elsewhere, while at Girdu Siah a conglomerate with typical "Hormuz" boulders occurs in the Lower Miocene.

There is no evidence to suggest that any salt-plugs rose early in the Eocene. A strange bed of red-coloured conglomerate, with dolomite and blocks of "Hormuz" igneous rocks suggestive of the debris from an exposed salt-plug, is a feature of the Upper Cretaceous of Kuh-i-Shamil. It is not absolutely certain, but

highly probably, that this conglomerate was derived from a decaying salt-plug that was exposed in Upper Cretaceous time. In the Middle Cretaceous nearby there is limestone-conglomerate of considerable thickness, which might possibly have been formed from the locally uplifted sheath-rocks of this plug before it breached them. A regional movement may however have been the cause of this conglomerate.

The evidence shows, then, that most of the salt-plugs broke through in post-Vindobonian, and probably post-Pliocene times, and that some were erupted either in Oligocene or Lower Miocene (pre-Vindobonian) times, while there is a strong probability that one at least was already exposed in the Upper Cretaceous. Others appear to be on the verge of bursting through to the surface at the present time.

In a few instances, the story is more complicated. For instance, Girdu Siah broke through in Oligocene times. It then appears to have been quiescent until Pliocene times, when it was again set in motion and caused faulting in post-Vindobonian beds on its northern side. Such occurrences as Kuh-i-Siah Taq-i-Girashi and Kuh-i-Namak-i-Shah Ghaib, in which a dome of salt caps the vent and a lobe of saliferous material has spread over the alluvium of the plain, indicate that upward movement of the salt in the vent is still going on at a rate sufficient to make good the ravages of weathering. In examples like Kuh-i-Ircheh, where only the cast of the salt-plug remains, movement of the salt ceased soon after final intrusion and the losses of weathering were not made good. In the type intermediate between these two, where the plug weathers down to a flat-topped hill as at Palangu and Kuh-i-Finu, upward movement of the salt has not been sufficient to effect complete compensation of weathering effects.

(52). Age of the Salt in the Salt-Plugs.—Since the first discovery by G. M. Lees of a trilobite in the debris from Al Busa salt-plug, evidence has accumulated from all over the country that the salt, gypsum, and red shales, which constitute the bulk of the salt-plug material, belong to early Cambrian, or possibly the pre-Cambrian.

While the saliferous horizons have not been observed directly, the lowest bed yet seen below the fossiliferous Middle Cambrian is a red sandstone, such as might be expected to follow in the train of saliferous red beds. There is no saliferous horizon between the Middle Cambrian and the Upper Cretaceous.

(53). "Hormuz Series."—In addition to blocks of rock belonging to a number of formations that overlie the salt-horizon, the "Hormuz Series" contains also blocks of igneous and metamorphic rock, and certain minerals, the origin of which is not so apparent.

(531). *Igneous Rocks.*—No igneous rocks have yet been observed in situ in the Persian Gulf salt plug province, although comparatively large areas of Palæozoic rocks have now been visited; yet the debris from salt-plugs frequently contains igneous rocks. It seems probable therefore that the igneous rocks are not younger than early Cambrian. Their comparative abundance suggests however that they lie in part above the salt-deposits.

(532). *Metamorphosed Limestone.*—The boulder of metamorphosed limestone with garnets must denote contact metamorphism either of Cambrian limestones or of limestones present in the late pre-Cambrian.

(533). *Pre-Cambrian Rocks and Minerals.*—A boulder of mylonite has been found containing abundant acid felspar and chlorite. This is probably a pre-Cambrian rock. Minerals, such as gedrite and iron-ores may readily be from the pre-Cambrian also.

(534). *Salt-"plucking."*—There is little doubt, therefore, that while the bulk of the "Hormuz Series" material is drawn from beds above the salt, a small percentage is derived from beds below it. The blocks plucked from below belonged probably to irregularities on the floor of the basement and were torn off during lateral migration of the salt towards a nucleus before vertical movement commenced. Once they were thus incorporated in the salt their transport to the surface would involve no difficulty.

(54). Plasticity of the Saline Materials.—One outstanding characteristic of the mixture of salt, gypsum, and clay which makes up the bulk of the salt plug material is its plasticity. It seems to be capable of flowing in somewhat the same manner as glacial ice. Under the high pressure it has punched circular holes through great thicknesses of hard competent rock, and under low pressures at the surface it has produced features simulating those found in glaciers. In both cases hand-specimens of the material, whether ice or salt, give entirely erroneous ideas of what their reactions to a long-continued, comparatively small force may be.

(55). Mode of Movement of Saline Masses.—Very little is known about the way in which the material in the salt-plugs moves. Laboratory experiments on the plasticity of salt have yielded results that are quite incompatible with its observed behaviour in plugs and "glaciers."

It seems possible that the amount of water present may be an important factor. In salt-plugs the presence of some water may reasonably be assumed, for salt-springs have been observed associated with many of the Persian occurrences. It is not known however, whether these are deep-seated or superficial.

As has been pointed out above, salt is seldom or never the sole constituent of a salt-plug in Persia. In some instances it is

subordinate to gypsum, and in others to red clay and shale. All these components also take part in the glacier-like surface-outflows. It may be, perhaps, that in the presence of a trace of water, intermolecular slipping and transference of material by solution and recrystalisation play important parts.

(56). CAUSE OF MOVEMENT.—About the end of the pre-Cambrian, or in the early Cambrian, salt and red shales were laid down in a basin, the floor of which remained quiet throughout the enormous periods of time during which the Palæozoic and a great part of the Mesozoic sedimentation took place. Thereafter much deposition still went on, but the region was no longer quiet, and one of the results of the unrest was to bring the salt from its original bed and gather it into long pillar-like masses reaching to the surface. No disturbance can be imagined to have produced this effect all at once: it must have been achieved in stages.

(561). *Formation of Nuclei.*—The unrest which is revealed in the geological record at the surface must undoubtedly have had also its deep-seated expression: while the sediments above were folded, the pre-Cambrian floor was probably cracked or warped. The salt and its associates lay in the zone between the rigid older rocks of the basement and the younger pliable rocks of the upper layers. As they were plastic, they would tend to move from positions of greater to those of lesser pressure. Any discordance between the shape of the basement and the beds above it would then encourage the salt to accumulate in thick nuclei separated from each other by areas of attenuation. In general the nuclei would appear where the beds of the roof were arched up, since there they would normally find the least pressure. But it is also possible to imagine that some irregular cracking may have allowed a block of the floor to subside, and there, too, the salt would find lower pressure and so form a nucleus.

The arches in the roof would be the deep-seated expressions of anticlinal folds at the surface, upon which while deposition was still going on there would be less material laid down. Consequently the pressure upon the arches of the roof would be less than that on the troughs, for these at the surface would be synclines collecting more and more sediment.

When further disturbance occurred it would find, therefore, incipient folds already formed at the surface and either warping or cracking in the basement furnishing lines of weakness that further snapping and folding would be predisposed to follow.

In the Persian Gulf province there was first a gentle movement in the Upper Cretaceous, followed by another about the end of the Oligocene, and then by a more vigorous one in the Upper

Miocene or Pliocene. The later movements would be unlikely to cause the formation of further salt-nuclei, but they would greatly increase the unevenness of the overburden, and may have contributed some of the pressure that was necessary to initiate eruptive movement of the salt.

(562). *Intrusion.*—The salt having once tended to accumulate in nuclei was subjected to differences of static pressure as has been mentioned. As it continued its flight from pressure it would press on the tops of the arches and penetrate any breaks in an endeavour to escape. The effective pressure available for driving the salt upwards would of course be the excess of the load of some 20,000 ft. of strata on the synclines over that on the arches—which may have been as little as two-thirds of the syncline load. Once upward movement had commenced, it would meet with less and less resistance, since the load of overlying strata would steadily diminish. On the other hand, progressive lengthening of the salt-column would involve great increase of frictional resistance to movement; and the weight of the column itself would also be progressively added to the resistance. No very large upward increase of velocity can therefore be attributed to the salt.

While the salt-mass may have started from the nucleus beneath with an irregular or angular cross-section, it would quickly assume the shape which could be driven upwards with least expenditure of energy when once it passed beyond the limits of the directing arch or fault. Thus it appears at the surface with a circular cross section.

It is suggested, therefore, that while the agglomeration of the salt from an even bed into nuclei was conditioned by tangential pressure manifested in regional disturbance, the chief factor in driving the salt upwards was irregularity of overburden or static pressure.

(563). *Shape.*—The normal throat of a salt-plug is approximately circular, this shape being the one which enables the salt to move with least expenditure of energy. It is only in these salt-plugs which outcrop in contact with the Eo-Palæozoic rocks that the shape of the intrusion is angular and irregular. Where they have been pressed through the Palæozoics and Mesozoics there has been time for this optimum cross-section to be established.

(57). Underground Salt Supplies.—The salt feeding the salt-plugs at the surface has been imagined as a series of underground lenses, concentrations in a once uniform bed connected in the main by attenuated sheets of salt. As the pressure increased it is reasonable to assume that the connection might eventually be completely severed. The salt-plug produced from such a lens would then be entirely dependent for its supply on one isolated

mass. If the supply were abundant, after breaking through to the surface the salt-plug might have enough material to repair wastage caused by weathering, and perhaps to supply a saline "glacier" as well. The amount that could be squeezed out would depend also on the shape of the nucleus below, as more would probably be available for extrusion from a flat than from a steep-sided nucleus. If the size of the underground aggregation is small, when once the pressure has been relieved, and the plug has burst through, the supply may fail, leaving no reserve to replenish wastage. Erosion and solution may then convert the upper part of the pipe into a cauldron.

It is possible to imagine that a nucleus may have segregated and fed a plug in the early Kainozoic and the reserves have become exhausted before the later movements; or that later movements may have initiated further lateral migration of salt, and so provided new supplies for extrusion—as seems to have happened at Girdu Siah.

There may also be areas in which the salt-bed in approximately its original condition remains in a kind of terrace-structure. This could happen between nuclei.

(58). Static Equilibrium.—Where a salt-plug has broken through and built a mound which stands up above the level of the surrounding country, it may happen that this is in static equilibrium; and as the weather tends to reduce the height of the hill a little more salt will be squeezed out to make good the wastage. The depth of the nucleus in the case of most Persian salt plugs is probably about 18,000–25,000 ft., so that the salt-hill should have a relief of about 2450-3400 ft. above the average level for approximate static equilibrium, since the salt has a specific gravity of about 2·2, and the column of sediments an average specific gravity of the order of 2·5. These heights are of the order observed for instance at Kuh-i-Namak-Shah Ghaib, although in most cases it would be difficult to choose a datum-line for the average level of the neighbouring sediments.

(59). Volume of Salt Involved.—A salt plug which emanates from a nucleus 21,000 ft. deep and has an average diameter of a mile and a-half (which is the order of size of many of the Persian salt-plugs and the approximate average depth of their origin) would have its salt requirements satisfied by the salt contained in a bed 150 ft. thick over a square with a 16-mile side. This would allow of sixteen salt-plugs of this size per degree square. The salt-plugs are of this order of density in the south-east over several thousands of square miles. The amount of salt required to build "glaciers" is only about one-twentieth of that required to fill the throat, and could be allowed for by assuming a very slight increase of the area of the salt-bed allotted to each plug.

The only value of such figures is to show that no fantastic thickness of salt need be postulated to provide for all the salt which has gone to form salt-plugs in Persia. A few miles east of Lar, where the plug-density is greatest, the salt needed could have been contained in a bed not more than 300 ft. thick.

To the north-west, where the number of salt-plugs is greatly diminished, there is probably a thinning of the original salt-bed; and where the salt plugs of the northern limits are found, the salt-formation has probably become little more than a saliferous red shale.

(6). Concluding Remarks.

In the foregoing pages attention has been directed almost exclusively to the activities and manifestations of the older salt-formation of Persia, the recognition and characterisation of which are the work of very recent years. There is, of course, another great accumulation of salt associated with the gypsum beds of the Miocene Fars Series. From drilling records it is known that this salt also shows aggregation into masses which may be regarded as incipient salt-plugs; and in at least one instance this Miocene salt has bulged and pierced the covering strata and is now visible at the surface. An adequate presentation of this topic would, however, overload the present discussion without clarifying very much the picture derived from a study of the older salt-complex.

It must be said, in conclusion, that the abundance and variety of Persian salt-plugs appear to be without parallel in any other land; and occurring as they do in an arid landscape, where exposures are abundant and good, they offer a unique opportunity for the study and elucidation of processes and phenomena that, only a few years ago, were frequently regarded as products of undisciplined imagination.

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Intrusive Salt Bodies in Coastal Asir, South Western Arabia.

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1. Introduction.—The American Stimulus.

The close connection between "salt domes" and important accumulations of oil, which is a feature of the Gulf Coast oilfield region in the U.S.A. and the intensive study of such phenomena which has been carried out by American geologists in this area, has created new and increasing interest in areas characterised by similar phenomena in the older parts of the world.

Isolated masses of salt have long been known in parts of Europe and Asia. They have received some attention from geologists in the past but, being only of minor importance from an economic point of view, the resulting studies have been regarded as of a like nature. With the connection established between "salt domes" and profitable oil accumulations the economic possibilities of these areas have increased and so, not only have the known occurrences been re-examined in the light of modern knowledge and requirements, but searches have been instituted for new "salt plug" areas.

It may be possible to say now, however, that, so far as the main object of these re-examinations and newly inspired researches is concerned, it would appear at present that America was fortunate in her "salt dome" areas and that the presence of "salt-domes" in other parts of the world does not necessarily connote profitable accumulations of oil in close association with them.

2. The Persian Gulf and Red Sea Regions.

The most interesting recent studies in connection with "salt dome" phenomena are, perhaps, those which have been carried out in the neighbourhood of the Persian Gulf.[1]

Reference is made in some of these papers to reports concerning the existence of intrusive salt bodies under possibly similar and related conditions on the coasts of Asir near the southern end of the Red Sea.[2] During the past 30 years, buried masses of salt have

[1] An excellent bibliography of these is appended to Mr. J. V. Harrison's paper "On the Geology of Some Salt Plugs in Laristan." *Quart. J. Geol. Soc.*, 1930, LXXXVI, p.p., 519-520.

[2] Ibid p. 512 and Dr. G. M. Lees, "The Geology and Tectonics of Oman and Parts of South Eastern Arabia," *Quart. J. Geol. Soc.*, 1928, LXXXIV, 590-591.

been studied in connection with the Egyptian oilfield area towards the northern end of the Red Sea. The relationships which may exist between oil accumulation and salt deposits in this region have also been investigated and the results published.[3] The great accumulations of salt which exist in the northern area are in the form of bedded deposits and do not provide us with the plug like structures usually indicated by the term "salt dome." Nevertheless geological domes are present and it is found that many of these have cores of salt and gypsum to which the apparent surface structure may be due, at least in part. It is possible that we have here incipient and early stages in "salt dome" formation, and this region is probably deserving of special attention on this account. Those interested should refer to the papers quoted for further discussion of origins and tectonic problems.

These northern Red Sea salt deposits are undoubtedly of Mid-Tertiary age conformably underlying strata containing Upper Miocene fossils. They are, therefore, part of a series of Miocene deposits, though it is possible that they may range down to the Oligocene.

In the coastal area of Asir[4] however, the more normal and orthodox "salt dome" features occur. True salt plugs which have been evidently forced upwards with and through the adjoining strata have been observed. It is quite certain that these salt masses are in no way related to those of the northern areas just dealt with. They are associated with types of strata which differ greatly, both in lithology and in age from the Egyptian types. It is much more easy to make comparisons with the conditions and materials of the Persian Gulf regions.

3. Investigations which have been made in coastal Asir.

Geologists and engineers, not many of them, have made some examination of this part of coastal Arabia. Before the War expeditions conducted by Turks and Germans may be referred to as well as the two solitary journeys made by the author himself. It is reported that the Germans actually did some boring for oil on

[3] Dr. W. F. Hume, "Oilfields Region of Egypt." Surv. Dept., Egypt, 1916, pp. 34 et seq. Also "The Geology of the Egyptian Oilfield. *J. Inst. Petr. Techn.*, 1921, 7, 408 et al.

The Petroleum Research Bulletins, Nos. 1 and 5, Ministry of Finance, Egypt, Cairo, 1918, should also be referred to.

[4] The whole of this area was formerly part of the Villayet of Yemen under Turkish Rule. It was, until recently, claimed as part of Yemen by the Imam of Sana. In a personal interview the Imam informed the author that the Farsan Islands were in Yemen. It is believed that Ibn Saud has recently disposed of this claim.

the Farsan Islands.[5] During the latter part of the War, French agents visited the region and made reports (unpublished). Since the War, technical parties, both American and British, have conducted investigations, and some actual and very recent drilling for oil has been carried on by a British concern also on the Farsan Group.

In spite of all the knowledge which must have been gathered by these parties of investigation, only one very recent and sketchy paper has, so far as the author knows, been published concerning any part of this area.[6]

The greater part of the year 1912 was spent by the author in carrying out, or in trying to carry out, geological work in coastal Yemen and Asir. To account for the inadequacy of the present paper, it is necessary to explain that in 1912 this area formed a Turkish province and that Turkey was at war with Italy. These coasts were therefore under blockade by the Italian Fleet. Although this is no place in which to describe the adventures of a petroleum geologist it may, perhaps, be said that the carrying out of the geological work referred to was greatly hampered owing to much of the time being spent as a prisoner in the hands of Italian, Turk and Arab.

Knowing, therefore, that detailed information, much more extensive, and probably accurate, is on record somewhere, and having both acknowledged and explained the imperfections which must exist in the present account of the area, we can go forward hoping that some of this preserved knowledge may be brought out in the subsequent discussion of the paper.

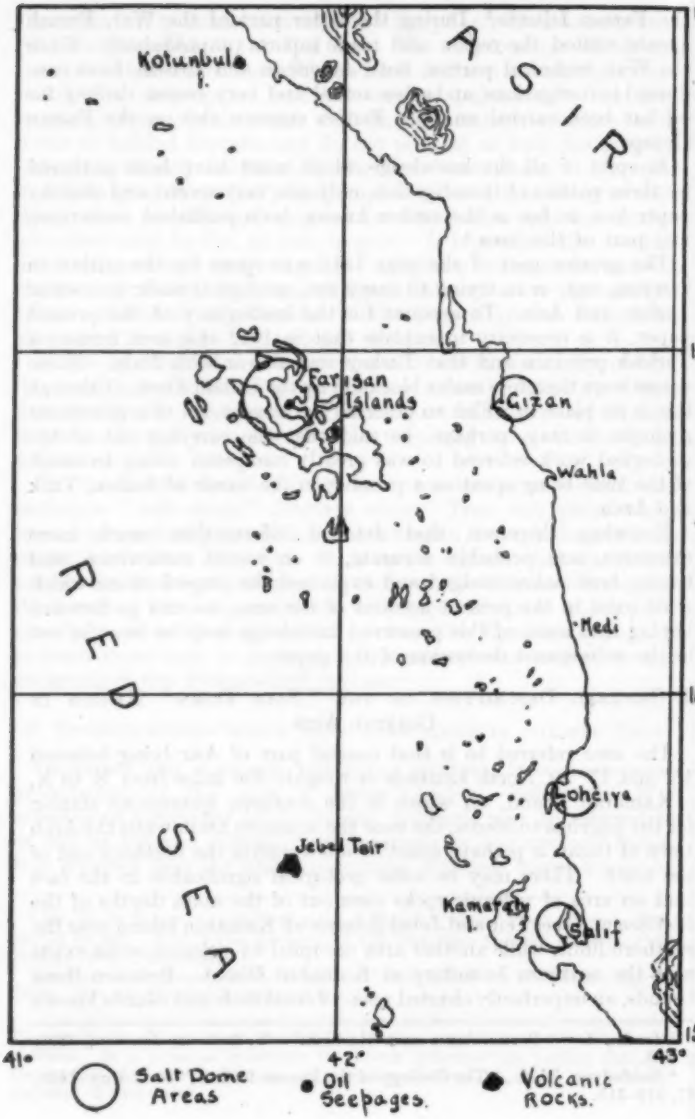
4. General Description of the "Salt Dome" Region in Coastal Asir.

The area referred to is that coastal part of Asir lying between 15° and 17° 30′ North Latitude or roughly 150 miles from S. to N.

Kamaran Island, on which is the southern quarantine station for the pilgrims to Mecca, lies near the southern limit, while the Arab town of Gizan is perhaps some 30 miles within the northern end of the tract. There may be some geological significance in the fact that an area of volcanic rocks rises out of the main depths of the Red Sea at Jebel Teir and Jebel Zebayir off Kamaran Island near the southern limit, while another area occupied by volcanic rocks exists near the northern boundary at Kotunbul Island. Between these bounds, an imperfectly charted maze of coral reefs and islands known

[5] Treat., I. "Pearls Arms and Hashish." V. Gollanz, London, 1930, p. 203.

[6] Macfadyen, W. A., "The Geology of the Farsan Islands," *Geol. Mag.*, 1930, 67, 310–315.


Kotunbula I.
ASIR
Farasan Islands
Gizan
Wahla
Medi
RED SEA
Soheiya
Jebel Teir
Kamaran I.
Salif
16°
17°
15°
41°
42°
43°
Salt Dome Areas
Oil Seepages.
Volcanic Rocks.

as the Farisan or Farsan Bank extends to a distance of some 50 miles westwards from the Arabian coast. The most important of these islands is the Farisan, Farsan or Fersan Group concerning which more will be said later. Another feature which may be of some geological importance is observable on the mainland between the limits mentioned. Rugged mountain ranges fringe the coasts north and south of the area. These coastal ranges disappear within the area itself. The gap so formed is occupied by a plain, which is broken only by hills, but through the gap, on clear days, the distant mountain ranges of the hinterland are visible.[7] This break has apparently a N.E.–S.W. axis. Salt domes are confined to the territory within this break and it is probable that many salt plugs remain to be discovered in this area.

So far as observed, the surface beds covering by far the greater part of this area, both islands and mainland, consist of coral reefs, uplifted coral and shelly limestones and sands and æolian deposits which range in age from Recent to not older than the Pliocene. The great development of strata ranging from the Cretaceous to the Miocene, the Nubian Sandstone, marls, massive gypsums, bedded salt deposits and Miocene Limestones so characteristic of the northern areas of the Red Sea, and in which the Egyptian Oilfields have been developed, appear to be absent in this area.

Geological structures are not pronounced and are masked in all but a few observed localities, though, in general, the structural trend lines which dominate the Red Sea area—*i.e.*, N.W. to S.E., are very obvious.

5. The Salt Intrusives.

Dr. Lees refers to the presence of intrusive salt bodies in this area, and gives the following localities: Salif, Loheiya and Guma.[8] In addition to these, salt plugs occur in the neighbourhood of Gizan[8] and on certain islands of the Farsan. An unpublished report by a Turkish official, dated over twenty years ago, mentions the occurence of a salt mountain which he calls Djebel Memlah on the Farsan Islands. A literal translation of his remarks is as follows: "Although there are two wells in the neighbourhood of Djebel Memlah (Salt Mountains), three-quarters of an hour distant, their water is bitter through the infiltration of oil." Subsequent work has confirmed the existence of "salt dome" formations on these islands. Bodies of salt are believed to exist on the Eritrean side of the Red Sea and certain features noted on islands of the Dahalak

[7] The Red Sea and Gulf of Aden, Pilot. 6th edn., 1909, p. 359, Loheiya.

[8] Loc. cit. Dr. Lees states that he obtained his information from Mr. Richardson, H. B. M. Consul at Bandar Abbas. Mr. Richardson was, for many years, H. B. M. Vice-Consul at Hodeida and therefore has a first hand knowledge of Yemen and Asir. The writer is, however, unable to trace Guma.

Archipelago, which lies exactly on a continuation of the bend or break of the gap on the Arabian side of the Red Sea, are almost certainly manifestations of the presence of salt cores.

PETROLEUM SEEPAGE ON THE FARSAN ISLANDS.

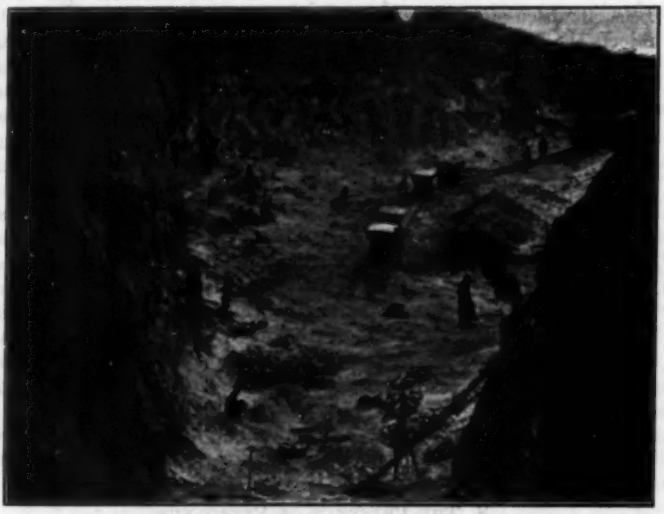
6. The Salt Plug at Salif.

The salt mass at Salif may, however, be taken as a type, and is perhaps the most accessible and important of these bodies. It lies on the mainland behind and a few kilometres to the eastwards of Kamaran Island. When visited, the salt was being mined by Arabs under a British engineer. It was being shipped to India, the profits providing revenue for the Commissioners for the Ottoman Debt, who controlled the undertaking. The salt mine is at a distance of a kilometre or so to the east of the village of Salif. It crops out in a structural ridge, the strike of which is discordant to the general trend line in the Red Sea. It is from N.E. to S.W. instead of N.W. to S.E., which is normal. The salt differs in colour from that associated with the northern areas referred to. It has a curious dark grey appearance. It has been well opened up by surface mining and forms part of the core of a sharp and assymetrical anticline or elongated dome which may, to some extent, be overfolded to the west, though this cannot be stated with certainty, as there was no opportunity for a proper examination

of the eastern flank. The salt outcrop is roughly oval in outline, with some elongation in the direction of the strike of the ridge in which it occurs. The greater part of the salt is said to be of great purity, and this was confirmed by subsequent laboratory tests.

Sketch Section across the Salt Dome at Salif.

On dissolving it with water, however, a little very fine insoluble sediment was noted. Under the microscope this proved to consist of well-formed microscopic crystals of anhydrite. The quality of the salt varied in the outcrop, so that part of the exposure was being left in place at the time of the visit.



THE SALT INTRUSIVE AT SALIF.

Evidence of the intrusive nature of the salt body is to be seen both in the mass and its surroundings. Between the mine and the village the strata forming the western walls of the mass are well exposed. They consist of beds of limestone, shale and conglomerates of a dark or slate grey colour similar to that of the salt itself. These beds are nearly vertical where they adjoin the salt

mass and dip in westerly directions at high angles which diminish somewhat as the village is approached. No evidence of fossils was observed, though the search for such evidence was inadequate. The beds seem to burst abruptly through the loosely consolidated cover which forms the normal surface formation. The whole occurrence seems to bear a strong resemblance to the similar phenomena noted in the Persian Gulf region and especially to those described by Richardson in S.W. Persia.[9] In a general way, the salt mass at Gizan also presents similar features but is associated with gypsum, shales and sandstones which Macfadyen is inclined to correlate with the similar deposits in Egypt.[10] This is a conclusion which must be accepted with reserve at present.

7. Probable Age of the Salt.

Examining the beds in the light of previous experience in the northern Red Sea areas, the author's 1912 note-book records an opinion that the beds are probably of at least Mesozoic age. Dr. Lees, in discussing the probable age of these salt plugs in Asir[11], rejects the Miocene on grounds already referred to, that no deposits of this age are known in this southern Red Sea area. He thinks that they may possibly be Cambrian, the probable age of the Persian salt bodies, but finally he decides in favour of a Triassic origin on the grounds that a lagunal facies of this age is known in Abyssinia to the S.W. of the area. Unpublished geological reports dealing with the Abyssinian side of the Red Sea indicate that the lowest stratified deposits resting on the old continental platform of Africa in this province belong to the Triassic period followed in places by a strong development of fossiliferous Jurassic limestones. This may be the case as far south as Madagascar, where similar conditions prevail, though in the southern parts of that island strata of Permian age have been recognised below the Trias[12]. The balance of the evidence at present available is, therefore, in favour of assigning these beds provisionally to the Triassic period, though an origin going as far back as the Cambrian is regarded as a possibility. So far as the author knows, however, the nearest exposures of older Palæozoic sediments are in Sinai to the north, the Sahara to the west, and the Persian Gulf area to the east.

8. The Presence of Petroleum.

Economically, the important question is whether these salt intrusives are accompanied by accumulations of oil. The question still remains to be answered, though the occurrence of seepages

[9] "Die Geologie und die Salzdome im Südwestlichen Teile des persischen Golfes." Heidelberg, 1926 Compare. Section on Tafel III.
[10] Loc. cit., pp. 314–315.
[11] Loc. cit., pp. 590-591.
[12] Wade, Madagascar, *J. Inst. Petr. Techn.*, 1929, 15, 12 and 26.

of petroleum in the area may be regarded as promising evidence. The Turkish investigator referred to mentions the occurrence of oil in the vicinity of a "salt mountain" on the Farsan Islands. In the course of two brief and difficult visits to these Islands the presence of active and considerable seepages of petroleum was confirmed, one group of seepages being noted on the northern part of Farsan Kebir and another on Farsan Seghir, a smaller island separated from the former by a strait so shallow as to be fordable. The strata in the neighbourhood consisted mainly of coral and shelly limestones and sands not older than the Pliocene and surface evidence of anticlinal folding on a broad and gentle scale was observed in at least two different localities. It may be said that structurally these islands offer more than one interesting problem to the petroleum geologist.[13]

Recent reports show that the drilling for petroleum recently in progress on these islands has been abandoned, though the reasons for this are not made clear in the statements which have appeared in the press. The following extract from a recently published work, the author of which is the greatest of living authorities on Arabia[14], throws new and important light on this matter, since it suggests that the field has been abandoned on political rather than on technical grounds :—

"And perhaps a more important, though incidental, result of the Wahhabi protectorate over Asir was that the potential oilfields of the Farsan Islands, recently leased by the Idrisi to the Asiatic Petroleum Co., now passed quite definitely beyond the reach of the Imam's most sanguine dreams. It is true that Ibn Saud accepted without demur the *fait accompli* of the Concession granted by the Idrisi but when the question of the transfer of its boring operations by the Company from one island to another arose in 1928 the Wahhabi ruler insisted on certain modifications in the terms of the original concession and the inability of the parties to agree on new terms resulted in the abandonment of the enterprise."

9. Conclusions.

It would appear, therefore, that in this part of Asir, of or South Western Arabia, we have an area in which potential oilfields, in some sort of association with "salt domes," may exist. It is a difficult country in which to work, politically backward and unstable, peopled by men who are by nature fanatical and unprogressive, suspicious of, if not actively unfriendly to, all foreigners and foreign influence. It forms part of an area which is almost unknown to the outside world, and it is only within recent years that the fringes of it have been investigated by geologists, the searching eyes of the great oil companies.

[13] See also A. Issel, "L'Origine et la Formation de la Mer Rouge," *Bull. Soc. Belge de Geologie, Palæontologie et d'Hydrologie, Bruxelles*, 1899, **13**, 65–84.

[14] Philby, H. St. John B., "Arabia," Benn, London, 1930, p. 336.

Some indications and many suggestions with regard to the tectonics of this area in general and of "salt domes" in particular will be found in the papers referred to, but no real geological detail is as yet available. With regard to this area, the author believes that evidence exists which tends to show a connection between these salt intrusives and lines of faulting tending from N.–S. to N.E.–S.W., thus cutting across the Red Sea rift faults, and coinciding, probably, with more conical trend lines. Insufficient attention seems to have been drawn to the fact that, in the Gulf of Mexico, Persian Gulf and Red Sea areas, "salt domes" are developed on the margins of important tectonic depressions; in coastal belts which constitute the fields of influence of major zones of fracture in the earth's crust. In fact, wherever "salt domes" occur, whether on the margins of such sea-filled fancy troughs or basins, or in areas not near to present day sea coasts the geological conditions with which they are associated are in a general way similar and kindred.

TYPES OF SALT DOMES (PARTLY THEORETICAL) ILLUSTRATING POSSIBLE EVOLUTIONARY HISTORY (WADE).

1. Original bed of salt.
2. Incipient buried doming or ridging.
3. Plug forming: salt moving towards surface along line of weakness.
4. Mature salt dome at surface with uptilted strata on periphery.
5. A later stage; planed down by erosion; position of salt mass at surface shown by solution depression.
6. "Dying" salt plug, disconnected with parent salt formation which itself may have disappeared or remain in vestigial form. Surface may be elevation or depression according to relative natures of "cap" and surrounding strata.